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VOLUME ONE

ENVIRONMENTAL EFFECTS OF NUCLEAR WEAPONS

By

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PREFACE AND ACKNOWLEDGMENTS

This paper is intended to pull together, update, and summarize work done over a three-year period. Much of the earlier work has been substantially revised and is, to that extent, now obsolete. However, some sections have been included in the present version with little or no change from earlier reports. The derivative sections, in order of appearance, are as follows:

Present Version (HI-518-RR)	Older Reports
Introduction (first half)	HI-388-RR, Introduction
Chapter IV, Section 2	HI-417-RR/V, Chapter V, in turn based largely on HI-243-RR, Chapter III, sections 1, 2 and Annexes B,C
Chapter IV, Section 3	HI-243-RR, Chapter III, Sections 3, 4, 5, and Annex C
Chapter V	HI-388-RR, Chapters II, III
Appendix E	HI-303-RR, Annex II
Appendix J	HI-243-RR, Chapter II, Section 1

Other parts of the present report recognizably overlap earlier work, although radically altered. Thus, Chapters I, II and IV (Sections 4 and 7) roughly follow HI-417-RR/V, Chapters II, III and VII respectively. Chapter III of the present volume is modeled after HI-417-RR/V, Chapter IV, which in turn evolved from HI-303-RR, Annex IV; and Chapters VI and VII grew out of HI-388-RR, Chapters IV and V.

Most of Chapter IV, Chapter VIII and, except as specifically noted, all of the Appendices and calculations are entirely new.

Mr. W. Davey collaborated with the author on Chapters II and III of HI-417-RR/V, to which, as already mentioned, our Chapters I and II owe some material.

Dr. I.J. Zucker of Battersea College of Technology, London, has collaborated with the author on the calculations given as Appendix B of the present report. It is our intention to submit this as a research paper to a meteorological journal, possibly together with Appendix C. Santa Scaffidi has also done some numerical calculations.

Others who have contributed substantially to the basic data compilation and presentation include Althea Harris, Corinne Enders and Cecelia Consorte.

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The above list is far from complete, but it is fairly representative. None of the above is, of course, responsible for the contents or point-of-view of the report.

ERRATUM

The figure of 100 MT's test explosions at Bikini and Eniwetok in paragraph 2, page 1-59 is misleading. The total reported yields of all atmospheric nuclear tests carried out by all nations through 1962 was 511 MT's, of which 105 MT's were surface bursts and the remainder were airbursts.* Presumably something less than half of this total was accounted for by U.S. tests, which up to 1958 were mainly carried out at Bikini and Eniwetok. Hence, the overall figure of 100 MT's is probably a reasonable estimate; however, most of the tests were actually airbursts, which would have produced no significant fallout to affect local vegetation. The megatonnage of groundbursts has not been announced, but it was presumably very much smaller--perhaps 25 or so.

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*Data from Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (1964), Table III, p. 46.

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INTRODUCTION

Several recent studies have indicated that, for a significant class of preattack scenarios, effective shelter programs are feasible within budget levels which are plausible under plausible circumstances such as a renewal of extreme cold war tension. Much of the remaining controversy over the utility of civil defense centers on the question of postattack recuperation. There has been a fair amount of speculation on environmental problems in particular, largely because the uncertainties in this area seem to be large or even unlimited.

It is fair to say that the general tenor of most of this speculation has been gloomy. In fact, among the writings of scientists with pronounced unilateralist or "anti-nuclear" sentiments, it is hard to find any statement about environmental problems which does not hint strongly at, or predict outright, an extreme disaster. Even analysts who have spent some time thinking about the problems fairly unemotionally, and who have had to temper their statements to satisfy a more critical audience, have been willing to entertain surprisingly catastrophic notions. The point is worth making, because it explains why it has seemed worthwhile to us to devote a section of this study (Volume II) to putting the problem into perspective by postulating, and analyzing, extreme cases. The following three quotations from highly respectable sources should be sufficient to justify this assertion.

1. ..."Therefore, depending on the geographical distribution, habits and sensitivity to radiation of various species, the various species, the various forms of life may survive the period of high radiation levels in drastically different proportions. And once the ecological balance is seriously disturbed, it is conceivable that the 'ecosystem' of the continent may exhibit a dynamics of its own that will carry it even further from the (proximate) prewar equilibrium. Some species, no longer controlled by their natural enemies, may multiply enormously; others, deprived of their normal sources of food or otherwise affected by the total change in the system, may disappear. Assuming that a rough equilibrium would eventually be re-established, there is no obvious reason to believe that it would closely resemble the prewar equilibrium."

   S. Winter, "Economic Viability after Thermonuclear War: The Limits of Feasible Production," RAND RM-3436-PR, pp. 135-136.

2. "Nuclear war might conceivably lead to complete sterilization of life in a particular area because of fire and radioactivity. Or there could be a selective removal of one or more essential biotic elements, which could have significant sequential effects (e.g., removal of higher plants leading to floods and erosion and followed by decreased agricultural output later).
   ...For instance, if two forms of life were in balance, if one was a predator on the other, and if you find that the predator was very radiosensitive, you might kill that one and then the other organism would flourish."

   <u>Civil Defense Hearings</u> 1961, Subcommittee of Com. on Govt. Operations, House, August 1961. Quote: H.H. Mitchell, pp. 331-332.

> 3. "The other point of fallout is simply this: The effects on nature. Fallout would produce large numbers of sick plants. Sick plants are the ideal breeding ground for herbivorous insects, such as locusts, or many other types. In addition to this, fallout would greatly reduce the vertebrate predators such as the skunks and birds and so forth, which help keep the insect populations in check. It is not possible to predict which insects, although you can indicate some likely candidates. But if you go down the list of the problems we have now with insects and compare many of the little known ones which are potential problems, one can envision an assault on the plant cover which would make the locust plagues of Biblical times look like tea parties."
>
> Civil Defense Hearings 1963, Subcommittee on Armed Services, House, June-July 1963. Quote: T. Stonier, p. 4938.

In addition to the vague but apocalyptic suggestion that the "balance of nature" might be irretrievably upset, there has also been conjecture about the possibility of widepsread, uncheckable fires, catastrophic erosion and flooding, climatic change, and widespread epidemics.

We shall, in the present study, consider these possibilities seriously and examine the arguments pro and con as well as we can within the constraints imposed by lack of data and/or theory in certain areas. However, it is not altogether out of place to look also at some of the reasons why writers discussing hypothetical hazards often tend, at first, to exaggerate their seriousness.*

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*As an example of such bias, it may be of interest to recall a calculation cited in The New York Times (Sept. 19, 1946) which baldly stated that a single ounce of pure botulinus toxin would be "sufficient to kill every person in the U.S. and Canada." This story with its threatening implications for biological warfare received tremendous publicity; but the various caveats and uncertainties did not. Among the latter:

1. The estimated lethal dose was based on experiments with laboratory mice; it was assumed that the lethal dose for humans would be simply scaled up in proportion to weight. There is no direct evidence to date of the actual lethal dose for humans.
2. The experimental poison was injected intraperitoneally by syringe, the body's protective walls (skin and/or stomach lining) being bypassed. The protection afforded by these barriers is known to be very important, but not precisely or quantitatively enough to take into account in a calculation. Hence it was ignored. This method of innoculation is irrelevant to biological warfare.
3. Equal measured doses were assumed, with 100% efficient distribution to the entire human population and no duplication or wastage.

Obviously any realistic method of dispersing this amount of poison would produce far fewer casualties. But only a sophisticated and critical reader would immediately realize that various caveats, especially the third, make the entire calculation absolutely meaningless as regards any implications for biological warfare. In fact, an ounce of botulinus scattered to

To begin with, a journalist is more likely to get attention with a scare story than with a balanced, disciplined presentation of all the complexities and uncertainties. Even if the writer is a competent professional, not influenced by such motives, he may be tempted to concentrate his attention on the worst possible cases for "political" reasons--as, for example, to influence public opinion in favor of accommodation and against rigidity or bellicosity in international affairs. Many scientists (and others) believe deeply that war is less likely if people remain convinced that war means near annihilation, than if there is some reasonable hope of survival. From this emotional assumption it follows that any reduction of the starkness of the threat increases the probability of war--and therefore seems to some almost like treason against humanity. This questionable view is sufficiently widespread in the modern world to command attention.

However, even if the motives for investigation are scientifically "pure," i.e., to search for abstract truth regardless of practical or political implications, there is another pitfall: Scientists have an understandable propensity to concentrate on problems which they have the technical equipment to solve. Since "real world" problems are seldom soluble as such, they must be simplified by means of artificial assumptions. In the passionless search for knowledge-for-its-own-sake, there is nothing unreasonable about this procedure. The analyst solves his simplified "model" problem and then begins the tedious process of making corrections for factors which were, at first, ignored. After a while (if he is lucky) he can see the trend of the successive corrections, both in direction and magnitude, and can perhaps say something worthwhile about the real problem. If not, the simplified model has its own intrinsic interest and the analysis will be available as a starting point for other researchers.

When this procedure is applied to problems as complex as the effects of nuclear warfare on the environment, however, things tend to go awry. In the first place, the "soluble" models require exceptionally drastic simplifying assumptions. It is correspondingly more difficult to correct for factors which were left out, and although the direction of any particular correction is usually clear, its magnitude often is not; the sum of several corrections may even leave us in doubt as to over-all direction. The analyst often drops the problem at this point, i.e., with a quantitative calculation based on a totally unrealistic model, and a series of reasonably careful but non-quantitative caveats pointing out where the model departs from reality, but not by how much. Even a sophisticated audience is likely to be misled unless it is also disposed to be particularly skeptical (or hostile).

A significant point which should be better appreciated is that in the above and many similar cases the analyst tends to make a facile

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(footnote continued) the winds or dropped into a lake might produce no casualties at all, or 10, 1,000 or 100,000. We are inclined to suspect the latter figure as being too high for any plausible scenario, but this is still more than three orders of magnitude below the limit which was quoted in the newspaper article.

presumption that the calculated maximum value for some variable (e.g., casualties) will normally be of the same order of magnitude as the actual expected value (which cannot be calculated directly). This is an invalid inference. It would be easier to guard against misleading, and be better from the viewpoint of integrity, objectivity and informativeness, if analysts made a regular practice of stating the other extreme case also, i.e., the minimum value. In the example quoted in the footnote, the lower limit on the number of casualties which could be produced by an ounce of botulinus toxin is zero, hence the range of possibilities is 0 to 2 x 10^8. Unfortunately the lower limit is logically trivial, and the revised statement as a whole loses much of its interest. Moreover, it would be pedantic to invariably include lower limits where they are, as in this case, trivial. Some critical sophistication is, therefore, demanded of the reader, if he is to be spared an endless repetition of such caveats.

There is, of course, no reason why the expected number of casualties due to the dispersion of botulinus toxin should be near either extreme. Hence a calculation of the upper limit is interesting only if (a) one wishes to compare the lethal effectiveness of botulinus toxin with that of other poisons with which one has more experience on an "other things being equal" basis or (b) if the absolute upper limit is a conservative estimate from some pertinent point of view. It would be conservative, for instance, if one could argue that even if the absolute upper limit were achieved, the result (i.e., number of casualties) would be negligible in a certain context.

Returning to the subject of the present study, it seems clear that much of the gloom about environmental effects is attributable to the fact that the absolute upper limit is often easy to calculate--in fact, trivial, in the foregoing sense--i.e., infinity. Thus fires may conceivably destroy everything, epidemics may spread everywhere and kill everyone, the economic system may break down totally. But the expected value of damage from a given attack is very hard to calculate unless one knows a great deal about fires, epidemiology, economics, and so forth. Especially, one must know something about the factors which limit the spread of fires or epidemics, or cause a depression to "bottom out." A major objective of this study is to gain some understanding of these terminating or limiting mechanisms.

It must be emphasized, however, that the kinds of real world constraints which normally operate (e.g., to limit the destructiveness of a storm, or the spread of a fire, epidemics, or pest outbreaks) are rarely absolute. Rather, one typically envisions a severity vs. frequency distribution function having a form such that, beyond a certain point, increasingly severe instances are increasingly rare. The maximal case which need be considered for practical purposes might be defined as one of a magnitude whose corresponding frequency is such that no case might be expected in a "long" time.[*] The length of time one picks as a standard of comparison, whether a generation, a century or a millenium, is partly a function of the "average" frequency of comparable events and partly a question of the magnitude of the greatest such event on record. Thus one might think in terms of a generation for purposes of estimating a "maximal" hurricane, but 10 million years would be a short period to consider if one were concerned with estimating the worst possible ice age!

Having pointed out the characteristic weaknesses of some attempts to treat very complex "real world" problems by means of analytic techniques from the realm of engineering and physics, we must issue two warnings. In the first place, even the most sophisticated models cannot transcend the available "state of the art," which means the results are bound to be at least as uncertain as the basic data--which is, in turn, both sparse and unreliable. It is, however, incumbent on the end-user of the study to remain conscious, not only of the existence of theoretical uncertainties, but also of the practical implications thereof. The importance of this injunction can perhaps best be illustrated by means of an example: for some time after an attack on the U.S. the only information available to the central government as to the composition and location of surviving resources would be derived not from on-the-spot census or inventory-taking (which would be a very slow and difficult process) but from a computerized damage-assessment model in which crude available data on targets destroyed, weather conditions, etc., would be entered.[**] Two categories of resources would be effectively "lost"--at least, insofar as any contribution to overall national goals is concerned--namely, resources <u>actually</u> destroyed and resources which the damage-assessment model <u>calculates</u> to be destroyed (and which are not otherwise known to have survived). It is possible to envision a central planning group allocating resources to replace "destroyed" factories which actually survived the attack, while depending on the output from other plants which the model calculated to have survived intact but which were, in fact, demolished. Hence it is almost meaningless in the present context to characterize a model in terms like ± n% accuracy. What matters is the practical utility (or disutility) of a given margin of error. In some cases even a sizable percentage error may make no practical difference, while in other instances, such as the one described above, even a "small" error may be quite unfortunate.[***]

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[*] e.g., the practical upper limit for earthquakes corresponds to about 9 on the Richter scale. No quake of this magnitude has occurred since seismographic records have been kept, although several 8.9 readings have been recorded.

[**] This is the function of the NREC under the OEP.

[***] This fact may, in turn, have important implications for policy planning. Thus it could be used as an argument against the concept of central planning itself.

The other warning is directed at technical readers who may be tempted to apply standards of criticism to the study, similar to those which they would apply to "pure" research. It seems very clear, at least to the author, that such standards are inappropriate. In particular, one often has a choice between using incomplete, unreliable or unconfirmed data, or giving up any attempt to estimate magnitudes. From the scientific point of view it is bad form to build elaborate theoretical structures on shaky foundations--partly, no doubt, because it was just this type of intellectual activity which inhibited real scientific progress until comparatively recently in history. Most scientists recognize the need to make conjectures (if only to test them), but still tend to recoil from any but the most modest consideration of further implications until such speculation is somehow legitimized by an accumulation of raw data.*

Policy planners (the intended audience of this study) cannot afford such delicate sensibilities. One cannot rationally refuse to consider the actions one will take, in case some theoretical phenomenon occurs, on the grounds that the theory is speculative--any more than one can refuse to guard against future eventualities on the grounds that the future is uncertain. In fact, it is precisely <u>because</u> the future is uncertain that planners must hedge against a number of different (often incompatible) alternatives. Similarly, it may be necessary to hedge against a theoretical event just because the theory is good enough to raise the possibility but not adequate either to confirm it or to rule it out beyond a doubt.

Several of the models introduced in this study are intended to play such a role. It is, of course, gratifying to be able to arrive at an unequivocal answer of the form: "X" is <u>not</u> important (compared with "Y"). More often, the theory is only sufficient to suggest ranges of possible magnitudes which partially overlap the ranges of major interest or concern. This is a scientifically uninteresting kind of result, but from the policy planning viewpoint it may be quite useful to know that "Z" <u>may</u> be important in comparison with "Y"--for it raises the further question as to how well "Z" can be guarded against (in case it should occur), for how much money, etc.

The better the data and the theory, the fewer alternatives need be taken seriously. As the state-of-the-art improves, some possible risks will certainly be eliminated from consideration as the quantitative aspects become better known and the range of uncertainty decreases. Policy planners would have correspondingly fewer things to hedge against and, therefore, fewer demands on limited resources. Thus, up to a point, further research may have a very high leverage. On the other hand, once the question, "Is X important, compared with Y?" has been answered definitely, one way or the other, there is little or no payoff to the planner

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*The normal position in the sciences at present is that there exists much more data than theory. Theorists are kept busy trying to account for known data. Hence it is very rare for a theorist to suggest a new phenomenon before the experimentalists have found it.

in pursuing many details which would be of great interest to the scientist qua scientist. To the extent that further research might be worthwhile at all, it would probably have to be directed towards finding the best (and cheapest) means of counteracting "X." To do this one need often (though not always) know very little about "X" itself.

To conclude the introduction, a few methodological and organizational comments may be in order. Our approach can, perhaps, be described as follows:

abstract (vs. empirical)
aggregative (vs. narrowly focused)
statistical (vs. mechanistic)

The term "abstract" is not intended to convey a lack of concern with data, but rather, to roughly characterize our attitude when faced with situations where data is unavailable. This will be further clarified in a moment. The stress on the aggregative and statistical features as opposed to microscopic, mechanistic aspects, reflects a notion that the behavior of complex macroscopic systems cannot be inferred, on the basis of existing theory, from the behavior of their components, even though the latter is clearly relevant and important. If we imagine a hierarchy of levels of analysis, beginning at the lowest level with simple components, such as artifacts or living cells, and ranging through organs, organisms, populations, communities, ecosystems, human complexes (e.g., cities), human societies and civilizations, it is clear that problems whose main point of impact is at the upper end of the scale cannot be treated by starting at the bottom and analyzing "upward." On the other hand, the reverse approach, carrying the analysis from the higher levels of aggregation to the lower ones, makes still less sense. The only possible resolution of the difficulty is to work, in some fashion, both ways at once: for example, we shall frequently make assumptions about the form of a distribution function on the basis of general knowledge of the aggregated system, then working back to allow the parameters of the distribution to be determined by information at the component level. Thus the abstract model typically comes first (in this study), empirical data being introduced at a later stage to make the model as quantitative as possible, but seldom with sufficient detail and/or reliability to enable one to work back up the scale and suggest modifications to the model--although, in principle, this would be the next logical step.

The procedure we have followed incidentally has the advantage of suggesting which kinds of basic data will be the most useful, e.g., in the development of predictive models for ecology, fire research, pest control, flood control, etc. Above all, we need more information on relations between "dose" and incidence (or response)--e.g., mortality curves--for various generalized insults or disturbances to biological populations, communities, or ecosystems. We also need better information on the relationships between magnitude and frequency of various kinds of disturbance such as (spontaneous) fires, earthquakes, storms, droughts, floods, insect outbreaks, epidemics and so forth, under various sets of circumstances. From these data one can derive theoretical distribution functions whose significant parameters (mean, variance, etc.) tend to depend in various ways on the prevailing circumstances. From thence it is possible to develop models to make modest predictions about what will happen if the circumstances change in prescribed ways.

As a first step towards some of these goals, we have assembled existing data--both historical and experimental--on a number of kinds of environmental disturbance. Much of this material had never been collected in one place previously, although since the earlier reports in this series appeared, at least one more ambitious compilation (for insects) has been undertaken elsewhere. In some cases of particular interest we have sketched, rather simplistically, how predictive models for handling complex problems might be developed. The major models, and some of the data compilations appear as Appendices A through H to the two volumes of the report.

The chapter organization is probably self-explanatory. The first volume (Chapters I-IV) is devoted to direct and indirect effects of nuclear weapons at the lower levels of aggregation up to and including populations and ecosystems but not including human and societal aspects. The second volume discusses concepts of disutility (Chapter V), range and context (Chapter VI), environmental-economic considerations (Chapter VII), and possible countermeasures (Chapter VIII). Conspicuously absent, at this stage, is any real discussion of socio-economic problems of environmental recovery. Future studies will, however, emphasize these areas.

CHAPTER I

PRIMARY RADIOLOGICAL EFFECTS

1. Origin, Characteristics and Distribution of Fallout

Although this subject is explicitly covered in an official AEC-DOD publication,*[1] there are a number of important points where the discussion in that document might usefully be supplemented. This section will not attempt to cover all the topics which might logically be subsumed by the heading, but will concentrate on a few key issues.

The central question, to which a great deal of experimental and theoretical effort has been devoted, is essentially as follows: given a nuclear explosion of yield W, and specified altitude, wind conditions, etc., what dose rate will be measured by a suitable instrument at a particular nearby location and subsequent time?** In its general form the question is too complicated to tackle directly, so various simplifying concepts have been introduced.

One such concept is total activity. It is now accepted that about 6 to 6.5% of the fission energy yield of a weapon is delivered relatively slowly in the form of γ and β radiation from fission products. The decay mechanisms are exceedingly complex: at least 200 isotopes of 36 elements are thought to be involved.[12] The major groups are listed in Table 1-1 and

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*Effects of Nuclear Weapons will be abbreviated to ENW in the following.

**Details of the morphology and time evolution of a nuclear explosion are an interesting subject in themselves but have comparatively little relevance to the ultimate radiological effects of the weapon except insofar as they determine the pattern of distribution of fallout. Very crudely, as is common knowledge, the isodose lines characteristic of fallout patterns are concentric ellipses pointing in the downwind direction.

It must be emphasized that the idealized patterns used in damage assessment calculations are based on one or another mathematical model. A number of such models have been developed. A detailed comparison would be a major undertaking with little relevance to our present task, but for purposes of identification the best known are as follows: ENW; Rapp et al. (RAND);[2] Pugh-Galliano (IDA-WSEG);[3] Anderson (NRDL);[4] AFCIN;[5] Technical Operations, Inc.;[6] Nagler-Machta-Pooler (Weather Bureau);[7] and Miller (SRI-OCD).[8] There are several alternate versions of some of these models, adding up to nearly a score of distinct cases. Several attempts have been made to compare and classify the various models, resolve discrepancies and/or clarify the reasons for them in terms of data base, physical assumptions, mathematical approximations, range of applicability, etc.[9,10,11] However, the results of these efforts are either inconclusive or unavailable and we shall therefore refer usually to the Miller model, which is the most recent and most detailed, and appears to have justified the least serious criticism (except that of being difficult to understand).

Table 1-1

Major Radioisotopes Produced in Fission

ISOTOPE	HALF-LIFE	AVERAGE β-ENERGY (mev)	γ-ENERGY (mev)	PROBABILITY OF NUCLIDE FORMATION PER FISSION (%)[13]	% OF CHAIN IN GAS FORM 35 Sec[14]	ABSORBTION[15]	CONCENTRATION[15]	ELIMINATION[15]
C-14	5600 yrs.	0.16	None	Induced activity		Complete	Protein, fat, carbohydrate	
Sr-89	53 days	1.46	None	2.56-2.93	100	Excellent	Bone	Very slow
Sr-90	27.7 yrs.	0.54	None	3.5	94	Excellent	Bone	Very slow
Y-90	2.5 days	2.27	None			Poor*	Bone	Very slow*
Y-91	58 days	1.54	1.19	3.65-3.76	n.a.	Poor	Bone	Very slow
Zr-95	65 days	(0.36,0.39,0.88)	(0.75,0.72)	n.a.	0	Poor	Bone	Slow
Nb-95	35 days	0.16	0.76	n.a.		Slight	Bone	Slow
Ru-103	7 days	(0.20,0.13,0.69)	(0.5,0.05,0.61)	5.2	(<65%)	Poor	Kidney	Weeks
Ru-106	1.01 yr.	0.04	None	2.44	n.a.	Poor	Kidney	Weeks
Rh-106	30 sec.	3.53	(0.51,0.62,0.87-2.66)			n.a.	n.a.	n.a.
Sb-125	2 yrs.	(0.3,.12-.62)	(0.35,0.42,0.60)	0.29	n.a.	n.a.	n.a.	n.a.
I-131	8 days	(0.61, 0.34)	(0.36, 0.28)	2.89	100	Complete	Thyroid	Month
Te-132	77 hrs.	(0.22, 0.9-2.1)	(0.23, .67-2.2)	4.24	60	n.a.	n.a.	n.a.
I-133	20.8 days	(1.3,0.4)	(0.53,0.85,1.4)	n.a.	n.a.	Complete	Thyroid	Month
Cs-137	30 yrs.	0.52	0.66	5.57-5.76	100	Complete	Muscle	Weeks-months
Ba-137	2.6 min.	---	---			n.a.	n.a.	n.a.
Ba-140	12.8 days	(1.02,0.48)	(0.03-0.54)	4.88-5.18	75	Good	Bone	Very slow
Ce-141	33 days	(0.43,0.57)	0.145	4.58	15	Poor	Bone, liver	Slow
Ce-144	288 days	0.30	0.13	4.42-4.69	0	Poor	Bone, liver	Slow
Pr-144	17 min.	(2.98,0.8,2.3)	(0.7,2.18,1.48)		n.a.	Slight*	Bone, liver	Slow*

*Information available only on other isotopes of the same element (chemically identical).

n.a. = not available.

Figure 1.1.[13,14,15] A convenient method of keeping track of the over-all process is in terms of individual atomic fissions resulting in the emission of γ-rays, measured in Curies (or Curies per unit area). As the radioactive debris ages, the rate of decay activity declines rapidly. at a time one minute after the detonation the activity level is currently calculated to be

$$5.5 \times 10^8 \text{ Curie/KT}$$

where each KT is assumed to be 100% fission.* This figure represents a change from the 1957 edition of ENW where the numerical coefficient was given as 3×10^8. The one-hour reference ionization dose-rate at a point three feet above an ideal flat plane, whereon fission products are assumed to be uniformly spread at a density of 1 KT/mi^2, can be calculated from the above by taking into account attenuation due to absorbtion by the air, as a function of γ-energy, and the fraction of total emission energy in the form of γ-photons. Averaging over the energy spectrum (partly observed, partly calculated), with an assumed mean at 0.95 Mev, a fairly straightforward calculation yields the conversion factor:[16,17]

$$3700 \; \frac{\text{Roentgens/hr at 1 hr}}{\text{KT/mi}^2}$$

excluding radioactivity induced by neutron absorbtion. The latter contribution is usually taken to be 200 $\frac{\text{R/hr}}{\text{KT/mi}^2}$,[18] but this is subject to local variations and, in any case, comparatively small.

In the 1957 edition of ENW, a smaller coefficient of 1250 was assumed. Shortly after the 1959 JCAE Hearings, where the old value was seriously questioned, Ralph Lapp carried out an independent analysis in which he concluded that the early ENW figure (1250 $\frac{\text{R/hr}}{\text{KT/mi}^2}$) was a lower bound, while the then-proposed NRDL value (3500 $\frac{\text{R/hr}}{\text{KT/mi}^2}$) was probably an upper bound.[19,20]. He rather arbitrarily proposed to split the difference and suggested 2000 as a reasonable compromise. However, the 1962 edition of ENW actually revised the number upward from 3500 to 3700 to adjust for a more accurate determination of the number of fissions per KT.[21] A comparison of several early fallout models in use at the time shows a startlingly wide variation in the conversion factors which were assumed (usually not explicitly, however). For example, Callahan et al. at Tech Ops analyzed the results of two OCDM attacks and three RAND attacks, and noted values ranging from 515 (OCDM, 6000-MT attack) to 2200 (RAND, 1700-MT attack), although it is not clear to what extent these figures included other factors such as ground roughness. Tech Ops itself used a coefficient value of 1580.[22] The original WSEG (Pugh-Galliano) model[23] assumed a factor of 2500, and later modified it to 2400 in line with an NAS recommendation. The Weather

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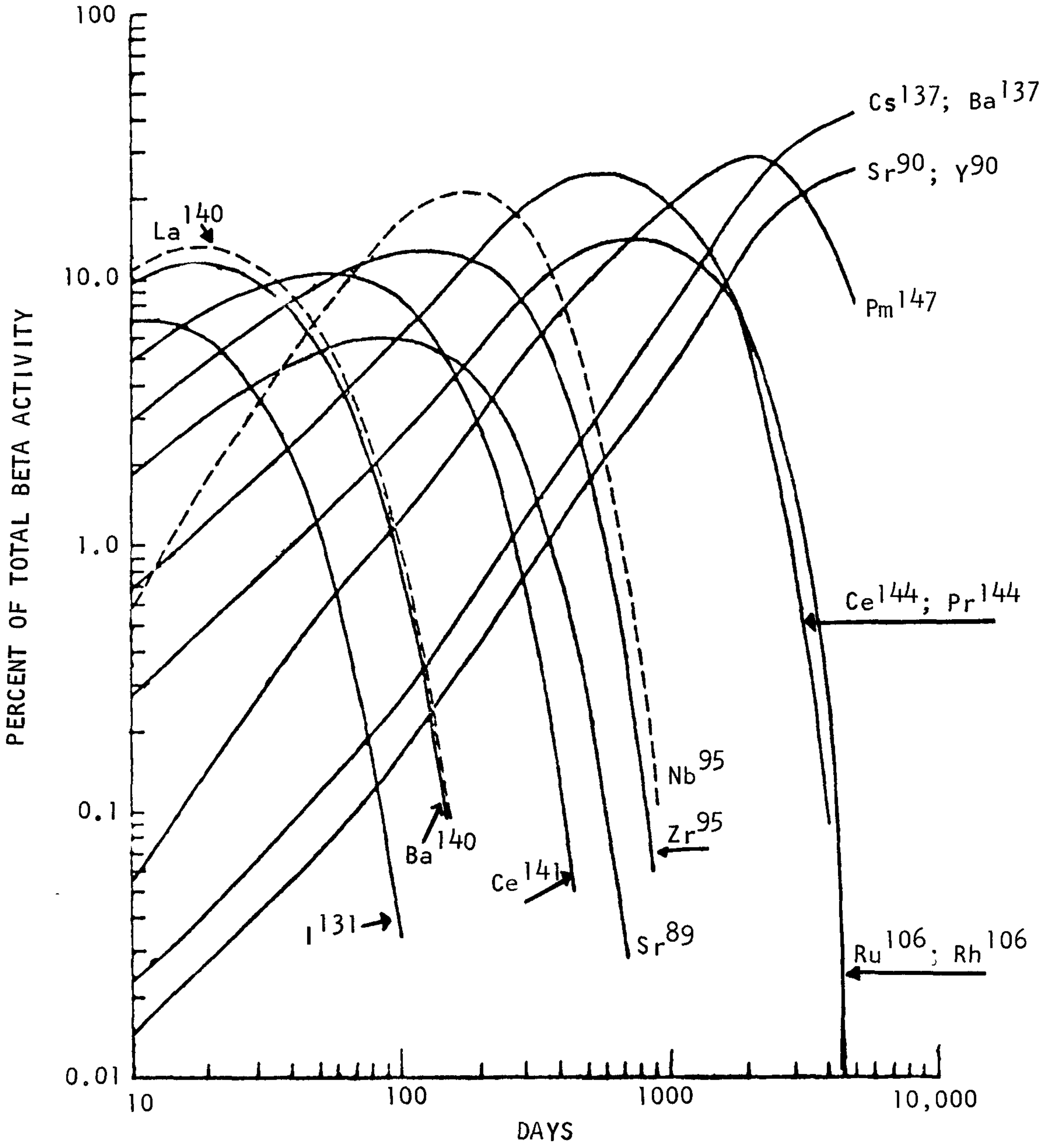
*It is customary to assume 50% fission and 50% fusion, although other combinations may occur in reality. The activity per KT would be halved in the case of a 50% fusion weapon.

FIGURE 1.1

DECAY OF A FISSION PRODUCT MIXTURE



Bureau fallout prediction "model"[24] used a factor of 2000. At the lower extreme, the AFCIN model,[25] developed by the USAF Intelligence Center (for the purpose of estimating damage to enemy target systems) assumed only 800 $\frac{R/hr}{KT/mi^2}$. Of course, the Miller-NRDL models are consistent with the "standard" conversion factor of 3700, as (presumably) are modern versions of the other models. However, it is well to be aware of the diversity of earlier assumptions in this regard, since (although the models in question are not currently used) the results of simulated attacks using different models are still cited from time to time for various purposes, e.g., Appendix A.

The proportion of total activity produced by MT class "groundburst" weapons and not deposited locally, i.e., in "world-wide" fallout, was estimated in the 1957 edition of ENW as 20%. In the 1962 edition the estimate was revised to 60% local and 40% world-wide.[26] However, there is now some reason to think the adjustment should have been even more radical: one possibly more nearly on the order of 40% local, 60% world-wide. For later reference in this report, the current ENW figures will be used, although it is important to bear in mind that future estimates may change.

One implication of the suggestion that world-wide fallout might account for a larger fraction of activity than previously thought, would be that a greater fraction of nuclear debris consists of very small particles. One can test the current theories of fireball thermodynamics and radionuclide fractionation against an independent set of nuclear test data. In the Miller model the mass per unit activity is derived in terms of weapon yield W and a function of the ratio of wind speed and vertical drift velocity (trajectory slope).[27] This ratio is an index of particle size. It is convenient to consider the inverse of this function, which has units of $\frac{R/hr\ at\ 1\ hr}{mg/ft^2}$. Evidently the activity per unit mass is about 10 times greater for particles less than 40μ in diameter than for particles of 400μ in diameter. The relevant test data are classified, but anyone with appropriate access can easily plot experimental points against the theoretical curves shown in Figure 1.2.[28] The activity per unit mass evidently rises very sharply as the particle size decreases. This is essential if a small fraction of the mass is to account for more than half of the total activity.

The standard picture would also have to be modified in another way. ENW does not discuss particle-size distributions explicitly, but the treatment actually assumes a log-normal particle-size distribution of the form

$$n(r)dr = \frac{1}{\tau\sqrt{2\pi}} \exp\left[-\frac{1}{2\tau^2}\left(\ln r/\bar{r}\right)^2\right] d \ln r.$$

Such a distribution was first inferred by Rapp at RAND from close-in Bikini test data (for large particle sizes), which suggested the values $\tau = 0.69$, $\bar{r} = 44.7$ microns.[29] A theoretical derivation due to Stewart[30] also predicts a closely related log-normal form. An alternative theoretical derivation led to the suggestion by Magee[31]

$$n(r)dr = \frac{1}{\bar{r}} \exp(-r/\bar{r})\ dr$$

Actually it is difficult to eliminate one or the other on the basis of available data for particles larger than 5μ, although they differ perceptibly at the low end of the spectrum where hard data have been scarce.[32]

More recent work distinguishes between the particle-size distribution in the stem and the mushroom. Thus a distribution function with two peaks (at $r = 40\mu$ and $r = 160\mu$) is suggested by Polan.[33] However, if 65% or so of the total activity is not deposited locally at all, it must be associated largely with particles less than 5μ in diameter, which strongly suggests the existence of still another peak in the distribution function for very small particles. One of the few unclassified sources of relevant but inconclusive data was the High Altitude Sampling Program (HASP), carried on using U-2 and B-57 aircraft from 1957 to 1961, especially--but not only--in connection with Project Argus ("Teak" and "Orange").[34] The question of particle-size distribution is primarily relevant for meteorological considerations, which are discussed further in Chapter III.

Determination of $\frac{\text{R/hr at 1 hr}}{\text{KT/mi}^2}$ for fission products distributed uniformly on an idealized flat smooth plane surface is not by itself an index of the actual dose to be expected at any given location as a result of a real attack. First, the actual distribution is far from uniform, but is characterized by a concentric series of roughly elliptical or egg-shaped isodose lines, stretched out in the direction of the prevailing wind(s).* Hence part of the activity is concentrated in regions of great intensity where it is wasted in "overkill," while part is distributed sparsely in areas where it is ineffective for the opposite reason. Moreover, fallout does not arrive everywhere simultaneously, so the reference dose at H + 1 hours is much larger than the average actual dose which would be received at a distance from the point of detonation even if the fission products miraculously distributed themselves uniformly. Some of the fallout (the "world-wide" component) is not deposited for months or years and can be ignored, for practical purposes, as regards external γ-dose. Second, the actual dose received by an object--such as a measuring instrument--three feet above the ground in a realistic environment will be less than the ideal due to the shielding effect of the object itself (which depends on its mass), ground irregularities, etc.

Each of these two factors gives rise to an "inefficiency" coefficient, or multiplier, which tends to increase the <u>actual</u> number of KT's (per square mile) needed to achieve a predetermined result over the <u>ideal</u> number based on uniform distribution, etc. The two hypothetical multipliers

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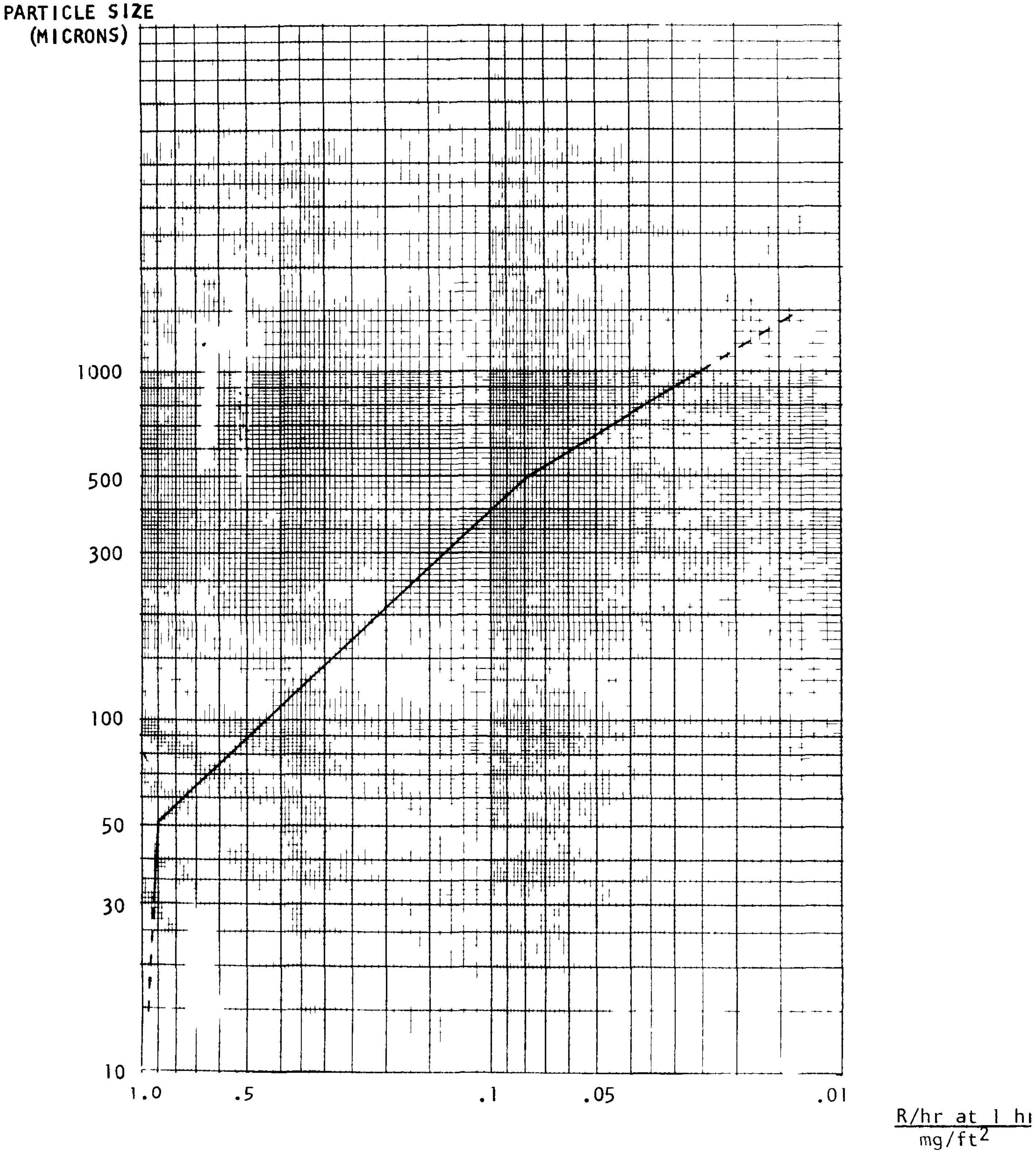
*Most fallout models (with the specific exception of the Weather Bureau model) assume something like a single average wind, or a single surface wind plus a "shear" wind at higher altitudes. Since this assumption is grossly oversimplified, idealized fallout patterns are far too symmetrical. In reality, the winds vary from altitude to altitude, from location to location, and from time to time. In addition, real fallout patterns include phenomena, such as isolated "hot spots," which are probably due to the effects of orographic features on wind circulation.

FIGURE 1.2

ACTIVITY PER UNIT MASS AS A FUNCTION OF PARTICLE SIZE



will be denoted Q_R and S_R respectively. The subscript R refers to radiological effects; similar multipliers Q_T and S_T will be defined subsequently in our analysis of thermal effects.

The first factor can, in general, only be computed for a particular location relative to a particular set of targets with a specified weather pattern and so forth. However, there is one special case where more general conclusions can be arrived at approximately, namely, where the weapons are exploded simultaneously at random over a large area. We would assert that this is not an altogether inappropriate model for considering widespread environmental (i.e., ecological) effects resulting from an attack on either military targets or cities. More detailed discussion and justification will be reserved for Chapter VI. Figure 1.3, derived in Appendix A, shows hypothetical curves for Q_R for two alternative optimum integrated 24-hour doses L: namely, L = 500R and L = 1000R. No attempt to justify these particular choices of L need be made at this point; curves corresponding to other choices can easily be derived by a similar technique.

The inefficiency Q_S due to shielding against γ-radiation is a more straightforward concept. It depends on "ground roughness," above ground level, shielding due to bulky neighboring objects such as buildings or trees, self-shielding, and shielding by the air (height above ground). The effect of ground roughness is usually assumed to cut the received dose (at a three-foot elevation) somewhere between 25 and 45% below the ideal level. Shielding by neighboring bulky objects is extremely variable, ranging from zero in an open field to 50% by the side of a sheer, isolated vertical wall, i.e., a large building. In a "canyon" such as Wall Street, shielding would be still greater. In a complex environment such as a forest, the effect is very hard to judge accurately, and would depend strongly on precise location vis-à-vis tree trunks, etc. Shielding due to air, as a function of altitude, is adequately discussed in ENW;[35] at six feet the reduction would typically be about 15%, while at thirty feet it would be about 40%.

Assuming an object roughly three feet above a "moderately" rough plane, in the neighborhood (but not immediately adjacent to) a few other bulky objects such as large trees, the actual dose relative to ideal dose, might be given by

$$(1-.35)(1-.10) \cong .59$$

which implies $Q_S = (.59)^{-1} \cong 1.7$. In the case of a peripheral meristem (i.e., growing point) of a tree, at a 30-foot elevation, the factor might be

$$(1-.35)(1-.10)(1-.40) \cong .35$$

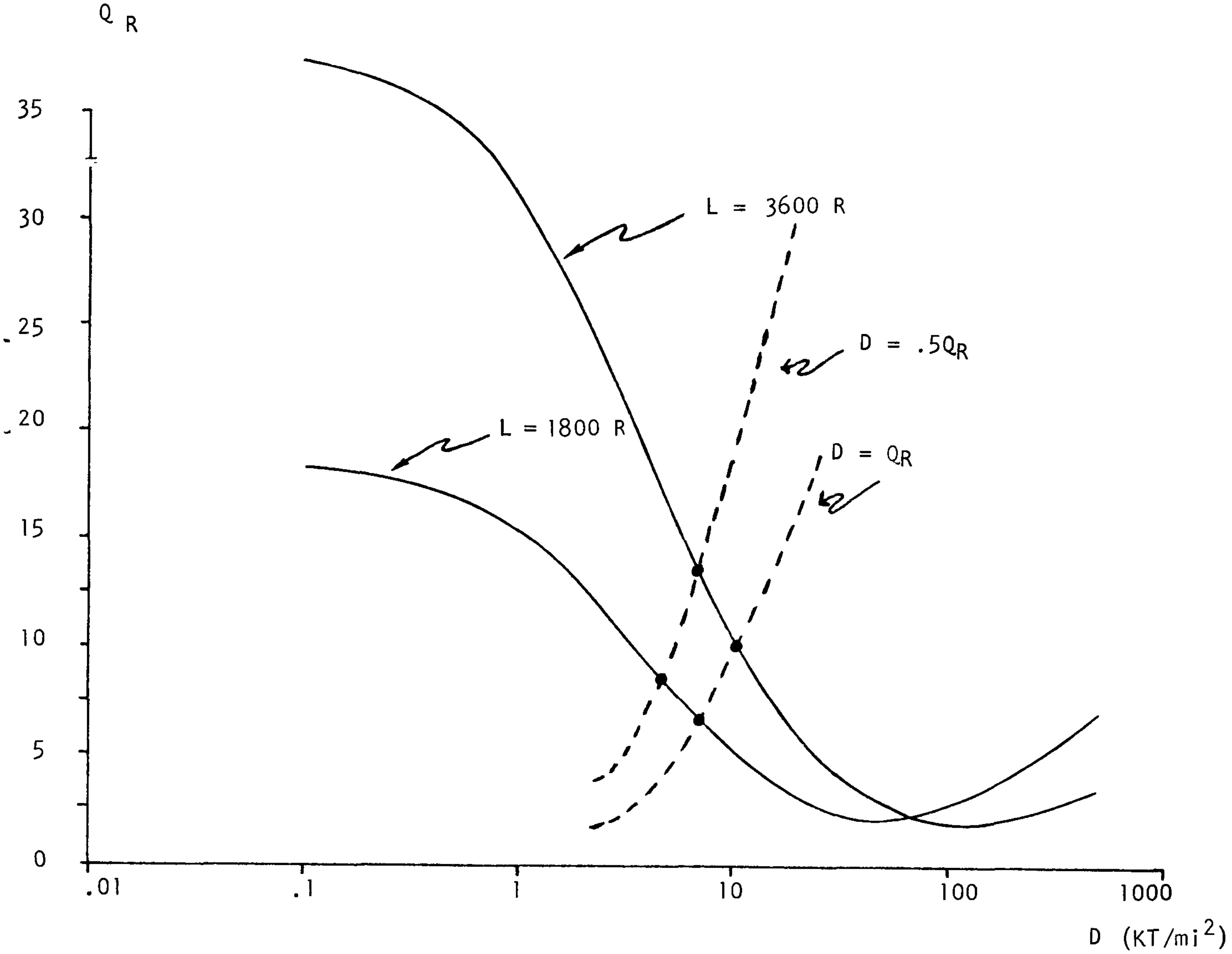
whence $Q_S \cong 2.85$. For a lateral meristem at the same elevation the tree trunk itself would provide additional (self-) shielding, i.e.,

$$(1-.25)(1-.35)(1-.10)(1-.40) \cong .26$$

$$Q_S \cong 3.8$$

FIGURE 1.3

RATIO OF TOTAL TO "EFFECTIVE" MT's FOR RANDOM ATTACKS OVER LARGE AREAS



Each of the component factors is uncertain by at least ±20%; their complements are uncertain by perhaps ±5% on the average; hence the Q_S's are uncertain by roughly ±20%, although it is unlikely all errors go in the same direction so the probable error is smaller. Disregarding artificial man-made environments, such as cities, or otherwise exceptional cases, it would appear that Q_S ranges in general between 1.5 and 4, with $Q_S = 2$ as a reasonable "average" value.

For certain kinds of objects, such as insects, small mammals and foliage in direct contact with fallout, the usual assumption, that external doses arising from β-radiation in fallout can be ignored, would not be valid.

On the basis of calculation and inference from the OCD-Miller fallout model, it seems likely that the total β-dose at a surface resulting from typical fallout at H + 1 hours would be about 100 times greater (in terms of energy absorbed) than the dose at the same surface from a γ-source one meter distant.[36] However, β-particles have comparatively little penetrating power and can be stopped by a few feet of air or millimeters of solid material. (A density of about 800 mg/cm2 assures about 98% absorbtion.) The β-dose through a shielding medium depends on the energies of the particles. Apparently most of the high-energy β's are emitted by fresh fallout, while later on the average energies decrease markedly.[37] Some field measurements with ionization counters indicate that the ionization from β-particles will be in the neighborhood of 20 times the γ-ionization at a distance of 5 cm. (in air) during the first day only. Subsequently, the ratio drops to 10:1 and 5:1 on the second and third days.[38]

A study, shortly to be published, based on the Miller fractionation model, derives β-dose contours for each of the major radioisotopes in the local fallout region.[39] When this work becomes available, some of the current quantitative vagueness should be cleared up.

One particular β-emitter, Sr-90, causes special concern because of its long radioactive half-life and its affinity for human bone. Data from Nevada shows that, for kiloton shots exploded relatively near the surface, the per cent of total Sr-90 deposited locally (within H + 12 hours) averages close to one-third of the per cent of total activity deposited locally.[40] The ratio between the two seems to increase somewhat as a function of yield. In the case of MT groundbursts, ENW estimates that 50% of the Sr-90 will be deposited locally. A more reliable estimate could presumably be obtained from the Miller model, but this calculation has not been carried out explicitly, whence, for the present, the above will suffice.

Sr-90 enters the biosphere in two ways: direct foliar absorbtion from leaves and stems of plants, and uptake from the soil via the roots. The amount absorbed in each case depends on the solubility of the Sr-90 atoms. It can be roughly assumed that the fraction of the radioisotope which condensed on the surface of fallout particles is soluble--and therefore potentially available to plants--while the fraction trapped within the glassy matrix of condensed fireball materials is permanently unavailable. Miller has calculated the number of soluble Sr-90 atoms likely to be deposited per square foot as a function of reference dose rates. These contour ratios can be expressed in units of

$$\frac{\text{soluble millicuries/mi}^{2*}}{\text{R/hr at 1 hr.}}$$

If we assume a standard 15-mph wind speed and a 1-MT (fission) explosion, then the Sr-90 activity contour ratio calculated by Miller is nearly constant and equal to

$$\frac{25\ \text{mC/mi}^2}{\text{R/hr at 1 hr}}$$

beyond 30 miles (with a peak at 38 miles followed by a slight decline) but drops rapidly to zero nearer to ground zero.[41] The 30-mile downwind point coincides approximately with the 2000 R one-hour reference isodose line. The following chart (Table 1-2) shows roughly how the soluble Sr-90 is distributed throughout two idealized patterns.

Table 1-2

Fission Products and Sr-90 Due to 1-MT Surface Burst

Isodose Contour (R/hr at 1 hr.)	Soluble Sr-90 per Unit Area (mC/mi^2)	Areas** Between Isodose Lines (mi^2)	
	Miller[42]	Miller[42]	ENW[43]
1-3	25-75	2600	4000
3-10	75-250	2400	5500
10-30	250-750	1800	4950
30-100	750-2500	1550	3250
100-300	2500-7500	1000	1000
300-1000	several thousand***	870	360
>1000	several thousand	-	340

A 1-MT fission-yield bomb is therefore capable of contaminating 4000 mi^2 of land to a level of 750 mC/mi^2 or more, and a further 10,500 mi^2 of land to a level of between 75 and 750 mC/mi^2 according to ENW. The Miller fallout model yields smaller figures, 3400 mi^2 and 4150 mi^2 respectively. Data presented in ENW indicates that particles falling from 53,000 feet in two hours or less would have radii larger than about 120μ and would carry roughly 8% of the activity deposited locally or 5% of the total.[44] Due to the tendency of Sr-90 to condense late in the evolution of the fireball, these large particles carry very little of the total Sr-90 produced by the bomb, of which still less (<< 1%) is probably in soluble form.

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[*] Using the equivalence relation:

$$\frac{10^{10}\ \text{atoms of Sr-90}}{\text{ft}^2} \Rightarrow \frac{5.94\ \text{disintegrations}}{\text{sec-ft}^2} = \frac{4.5\ \text{mC}}{\text{mi}^2}.$$

[**] The area estimates were made by means of a planimeter from the idealized fallout pattern published by Miller, and by using the standard formula for the area of an ellipse in the ENW case.

[***] In this region the contour ratio drops exponentially but the dose rate increases exponentially.

Referring now to the previous calculation for uniform distribution of fission products on an ideal flat plane, we find

$$\frac{\text{Soluble Sr-90}}{\text{R/hr at 1 hr}} \times \frac{\text{R/hr at 1 hr}}{\text{KT/mi}^2} \cong \frac{25\ \text{mC/mi}^2}{1/3900\ \text{KT/mi}^2} \sim \frac{98\ \text{C/mi}^2}{\text{KT/mi}^2}$$

This compares with

$$\frac{\sim 100\ \text{C/mi}^2}{\text{KT/mi}^2}$$

for all Sr-90 produced, if all fission products are included, which implies almost 100% average solubility. This seems to directly contradict some experimental evidence which has been published for close-in fallout. Most such measurements refer to the solubility of the total fission product mixture[45] rather than Sr-90 alone, which is largely confined to the surface layer of the fallout particles, due to its low condensation temperature.

The apparent discrepancy may also be due in part to a confusion between initial solubility and long-term solubility. The definition of "solubility" used in the published experiments may be somewhat unrealistic, to the extent that no attempt was made to duplicate the actual conditions in soil (other than adjusting the pH), where a number of catalytic agents (e.g., enzymes, produced by bacteria and fungi) help to break down chemical bonds. Many of these reactions go to completion very slowly. On the other hand, there are almost certainly ion-exchange reactions in the soil which go the other way, i.e., some initially soluble Sr-90 is precipitated in insoluble forms (especially in clay). Russell and Burton estimate 50% solubility for long-term residence in the soil, even making some allowances for these factors.[46]

The other major source of contradiction is, as mentioned previously, that we have imposed an <u>ad hoc</u> assumption (that 50% of the Sr-90 comes down locally) on Miller's results, whereas to be consistent we should use the figures predicted by his model itself. With the help of a little algebra it can be verified that the results quoted above are consistent with a 50% assumed solubility, if 75% of the Sr-90 is assumed to be in the world-wide fraction. As indicated earlier, figures in this range cannot be excluded on the basis of what is currently known.

We now wish to exclude the fraction of total fission products and soluble Sr-90 which are deposited (a) inside the 1000 R/hr contour, i.e., on particles with radii $>120\mu$; and (b) in world-wide fallout, i.e., on particles with radii $<10\mu$ or so. The first category accounts for about 5% of fission products and (we assume) much less than 1% of the soluble Sr-90. The second category accounts for ~40% of total fission activity and about 50% of the total Sr-90. Hence the ratio of Sr-90 to total fission products in the region of local fallout (particles with radii $10\mu < r < 125\mu$) is reduced to ~90% of the over-all ratio, and finally we obtain for the local fallout area beyond the 1000 R/hr one-hour contour

$$\frac{88\ \text{C/mi}^2\ \text{(soluble Sr-90)}}{\text{KT/mi}^2} \text{ for } 10\mu < r < 120\mu .$$

2. Radiation Damage Mechanisms at the Cellular Level

The achievements of biochemistry and biophysics in the past few years have helped to clarify our understanding of the complex chain of events initiated when cells are irradiated, although much remains to be learned.

One primary effect of radiation on living matter is simply due to the fact that organic molecules are broken up into radicals and ions. These fragments are typically unstable, i.e., they are chemically active. Thus radicals may interact with other radicals or with unaltered (and normally stable) molecules, producing chemical products which perturb the chemical environment necessary for cell functions to proceed. Free-radicals such as H^o, OH^o, arising from the splitting of water molecules, which constitute roughly 70% of the weight of a cell, are particularly important in the initial chemical changes induced by radiation. One of the reactions which apparently occurs is $OH^o + OH^o \Rightarrow H_2O_2$, while $H^o + H^o \Rightarrow H_2$. Thus, hydrogen peroxide and free hydrogen among other things will be present in irradiated cells.

All the essential constituents of cells, but especially complex molecules like proteins and polysaccharides, may be affected either through the action of such radicals or "daughter" products or they may also be injured by ionizing radiation directly. The respective roles of the direct and indirect action of radiation in bringing about cellular lesions is not yet clear; it is probable that in most cases both effects are operative, but that the first predominates.

Damage can also be caused by radioactive decay of an unstable radionuclide (isotope) which has become incorporated into some critical molecule. The exact location of such a nuclide in cellular structures may be important. For example, carbon-14--a nuclide with a very long half-life--decays by emission of a beta particle to the stable isotope nitrogen-14. The beta emission itself may obviously give rise to ionization effects. However, since carbon is a basic constituent of all essential living structures, it is also likely that the change of carbon-14 into nitrogen-14 will occasionally occur within a key molecular structure such as a gene. This change may, in some circumstances, outweigh the effects of the radiation released by that nuclide in the form of beta particles. Direct evidence regarding the consequences of transmutation of carbon-14 is still limited,* but local effects of disintegrations have also been postulated for other isotopes such as phosphorus-32.

Depending on the dose of radiation, chemical processes leading to the synthesis of essential cellular constituents are retarded to varying

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*Some will argue that one should not mention possibilities which have not been experimentally established. The point is, we are not advocating a theory but pointing out a possible hazard. If future research shows it to be unfounded, that is no reason for not discussing it as long as the possibility seems to be open.

degrees and may even be completely inhibited; this is particularly true for the synthesis of nucleic acids. The integrity of these synthetic mechanisms is essential for the maintenance of both morphological and functional characteristics and for ensuring growth and division of cells. Inhibition of mitosis (division) is, in fact, one of the earliest effects of irradiation, but probably most cellular functions and structures are to a greater or lesser extent impaired by radiation. Cellular death can ultimately be brought about by any one of several different mechanisms, including actual chromosome breaks.

One of the major long-term consequences of radiation is genetic damage, due to chromosome mutation or gene mutation. The former is the consequence of chromosome breaks. When two or more breaks are produced in the same or in different chromosomes, the unions which may occur frequently involve alterations of the original sequence or pattern of genes. Alteration of the gene sequence, as well as loss of parts of chromosomes or even of whole chromosomes, often leads to cellular death. In some cases, however, the chromosomal damage is simply transmitted to daughter cells.

The nature of gene mutations has been recently clarified by studies on bacteria and viruses. Nucleic acids--long chain molecules (DNA and RNA) along which genes are arranged within chromosomes--consist of a sequence of four elementary molecular units in various specific combinations and permutations.* Changes in the ordering of these units are tantamount to mutation (though not every such change is "allowed").

The mechanism of mutation is, however, far from being well understood. Studies in lower organisms have shown that mutation is a complex process going through a first stage in which the damage may, at least to a limited extent, be reparable, and only after a certain time becoming irreversible.

Like all radio-biological effects, the induction of mutations is dose-dependent and is proportional to the absorbed dose (rad) down to the lowest levels investigated so far. The proportionality factor, however, has been shown to vary with the dose rate in a number of species.

Correlations between measurable cellular characteristics of different species and vulnerability to radiation have been investigated experimentally in detail by Sparrow, _et al_.[47] Sparrow has unified many of the observed results in terms of a phenomenological model, called the "target-size theory," which is based on the approximation that the substance of the cell nuclei--containing the chromosomes--is uniformly vulnerable to ionizing radiation and that, by comparison, the rest of the cell is immune. This approximation apparently has a considerable degree of validity; at least it has led to a series of useful unifying mathematical relationships which allow one to predict the vulnerability of any particular kind of cell to radiation in terms of easily measured quantities such as nuclear volume or DNA-content. The accuracy of these predictions seems to be of the order of ± 25%.

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*The genetic "code."

The target-size theory states that the probability of damage to quiescent cells* is approximately proportional to the cell nuclear volume per chromosome, allowing for small discrepancies due to other factors. Figures 1.4 and 1.5[48] illustrate the important relationships. Specifically, it appears that the lethal dose, in terms of energy absorbed, is about 3.6 mev or 5.8×10^{-6} ergs per chromosome. This conclusion is still tentative, but has been verified for species with very wide variations in lethal dose, chromosome numbers and cell volume.[49] Nuclear volume has been found to correlate very closely in the species with average DNA content,[50] which may be the more fundamental variable.

Measurements of nuclear volume have been made for many plant species. Although no strict correlation has been observed between nuclear volume and taxonomic group, Sparrow and Schairer have noted that many species of gymnosperms (principally conifers) and monocotyledonous angiosperms have nuclear volumes greater than $400\mu^3$ ($\mu = 10^{-6}$meter), while relatively few dicotylae have such large nuclei.[51] The distribution of interphase chromosome volumes (i.e. total nuclear volume/number of chromosomes) and calculated radiosensitivities among 87 species of gymnosperms is shown in Figure 1.6. The corresponding distribution for 85 species of dicotylae is given in Figure 1.7.[52] Deciduous trees and most economically valuable plants except the grasses and cereal grains (Gramineae) are dicotyledonous.

There are a number of other factors which must be taken into account in order to refine the predictions made by this theory, of which the most important are as follows:

1. Ploidy: Sometimes the chromosomes within the nucleus duplicate themselves, but the cell as a whole does not split.** If the nucleus contains two copies of each chromosome (the normal situation), it is called a diploid. A cell, e.g. sperm or ovum, with a single set is haploid.*** If more than two copies exist, it is called polyploid. Polyploidy seems to somewhat increase radiation resistance compared to diploidy. This is intuitively understandable, since damage to one of the chromosomes may not prevent the functions controlled by that chromosome being carried out in the nucleus. The average protective effect for eight pairs of polyploid species differing by a factor of two in chromosome number is 1.67.[53] However, there are some contradictory results, particularly for polyploid strains of yeast and the wasp, Habrobracon, at certain stages of development.[54]

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*Cells not actively dividing.

**This process can be induced artificially by using the biologically active chemical colchicine. It is of use in producing true-breeding, fertile hybrid species, for example.

***Haploidy is a special condition related to sporogenesis in plants or zygogenesis in animals. The process of fertilization (in sexual reproduction) results in haploid cells becoming diploid, with contributions of one set of chromosomes from each parent.

FIGURE 1.4

LETHAL DOSE AS A FUNCTION OF CHROMOSOME VOLUME

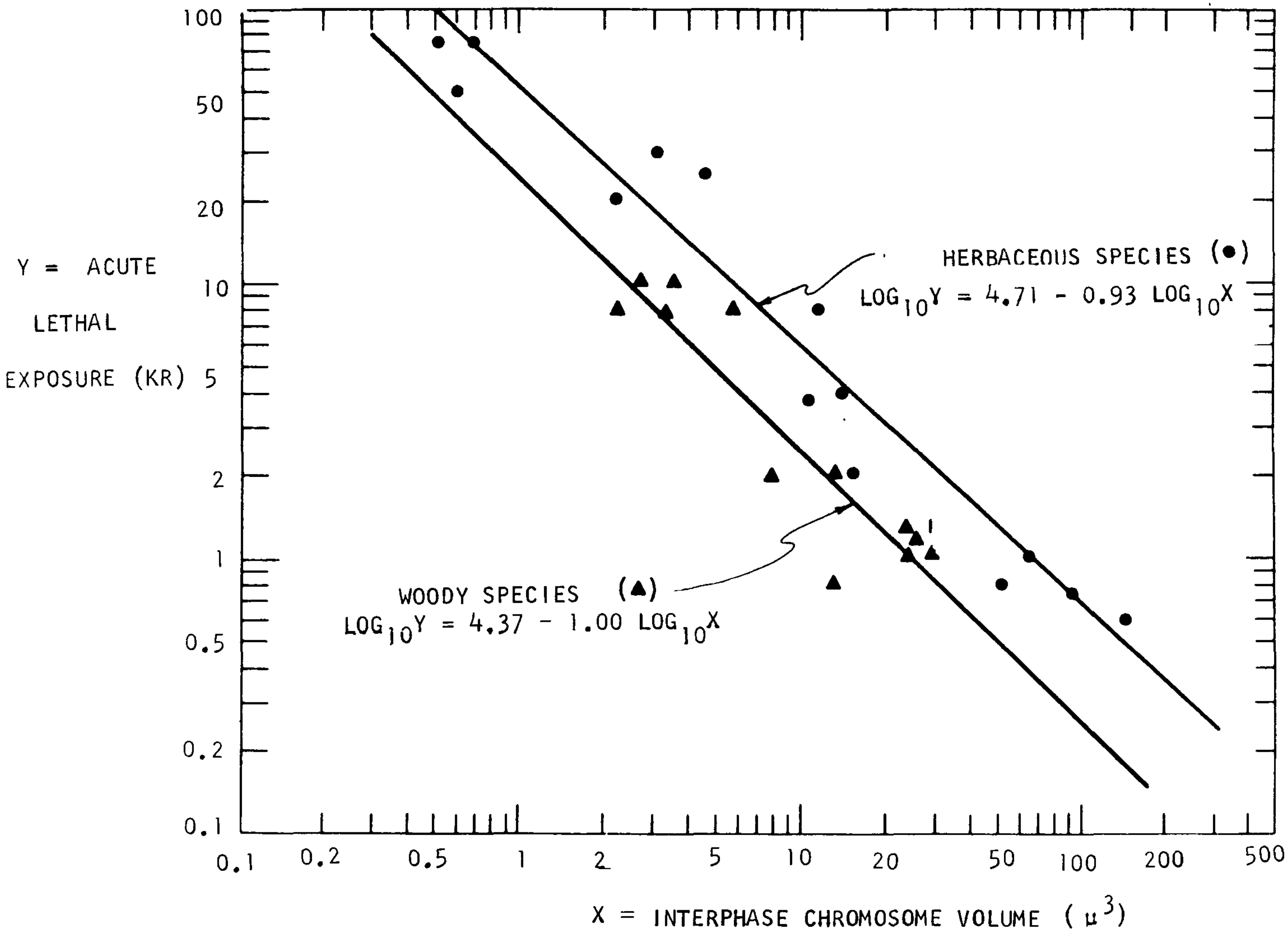


FIGURE 1.5

DOSE PRODUCTION GROWTH AS A FUNCTION OF CHROMOSOME VOLUME

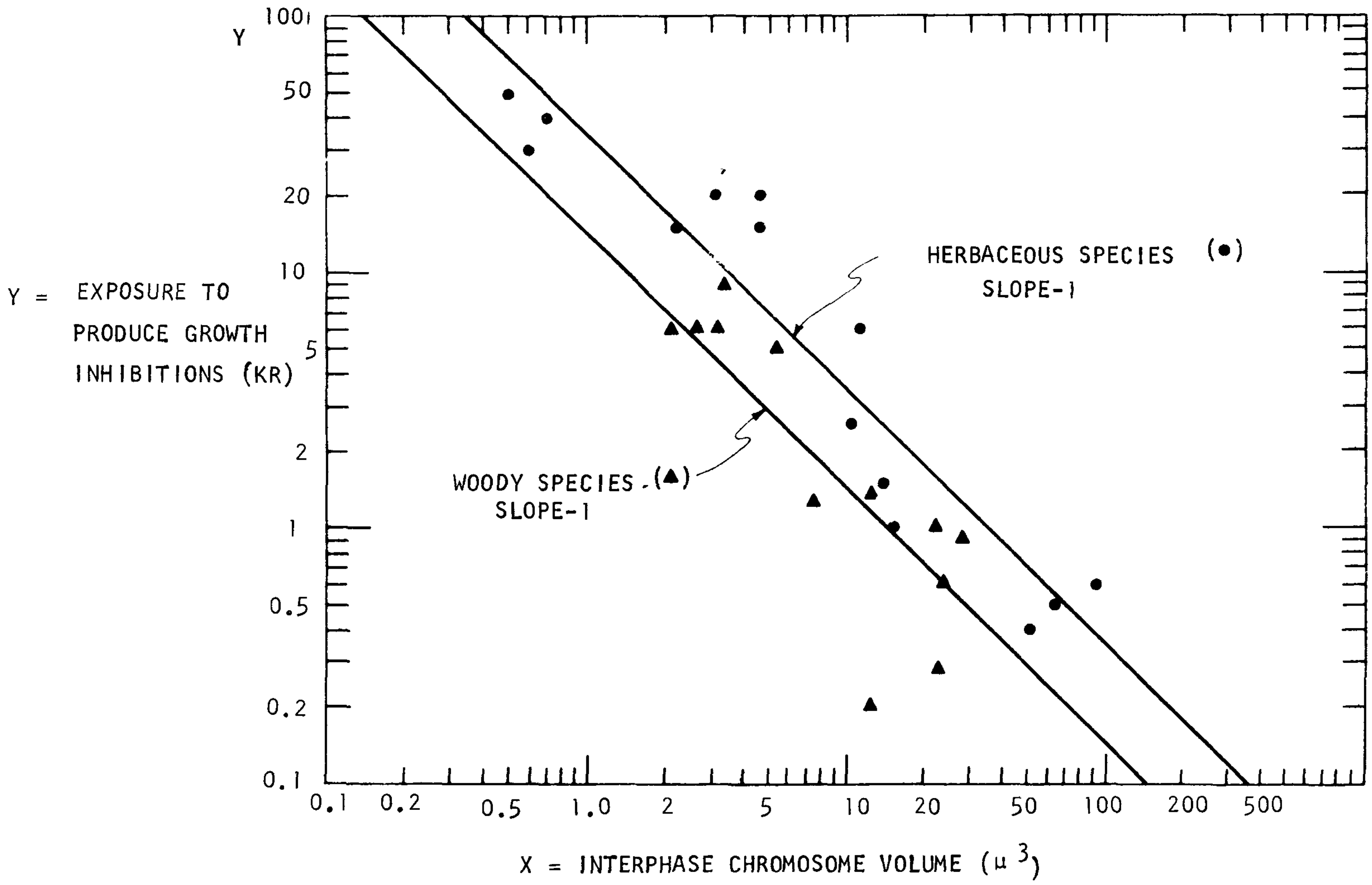
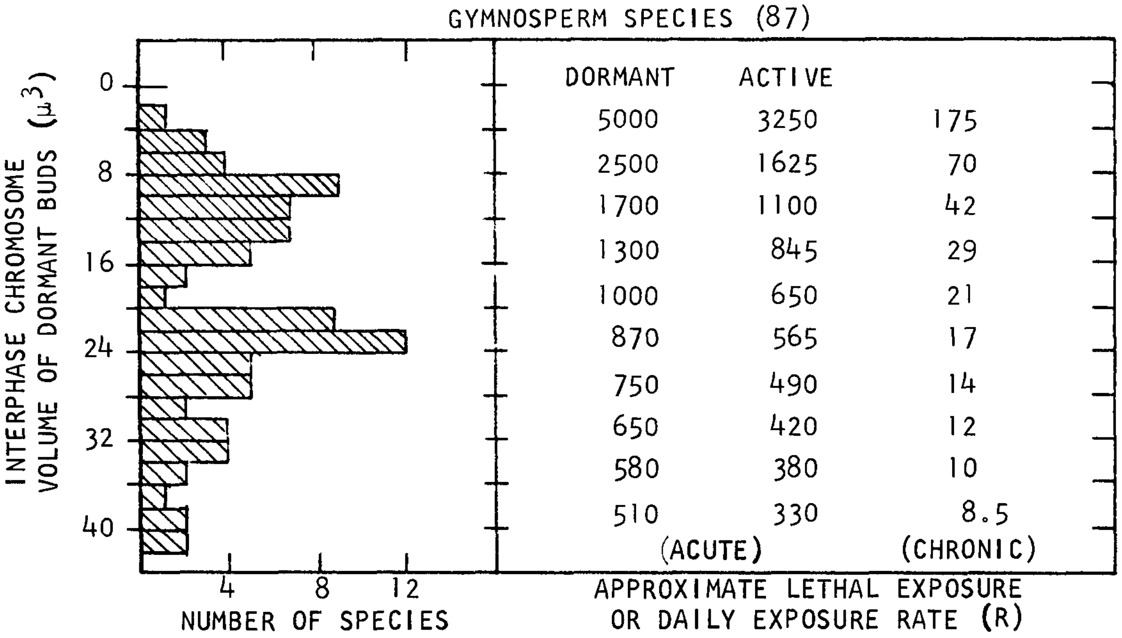


FIGURE 1.6



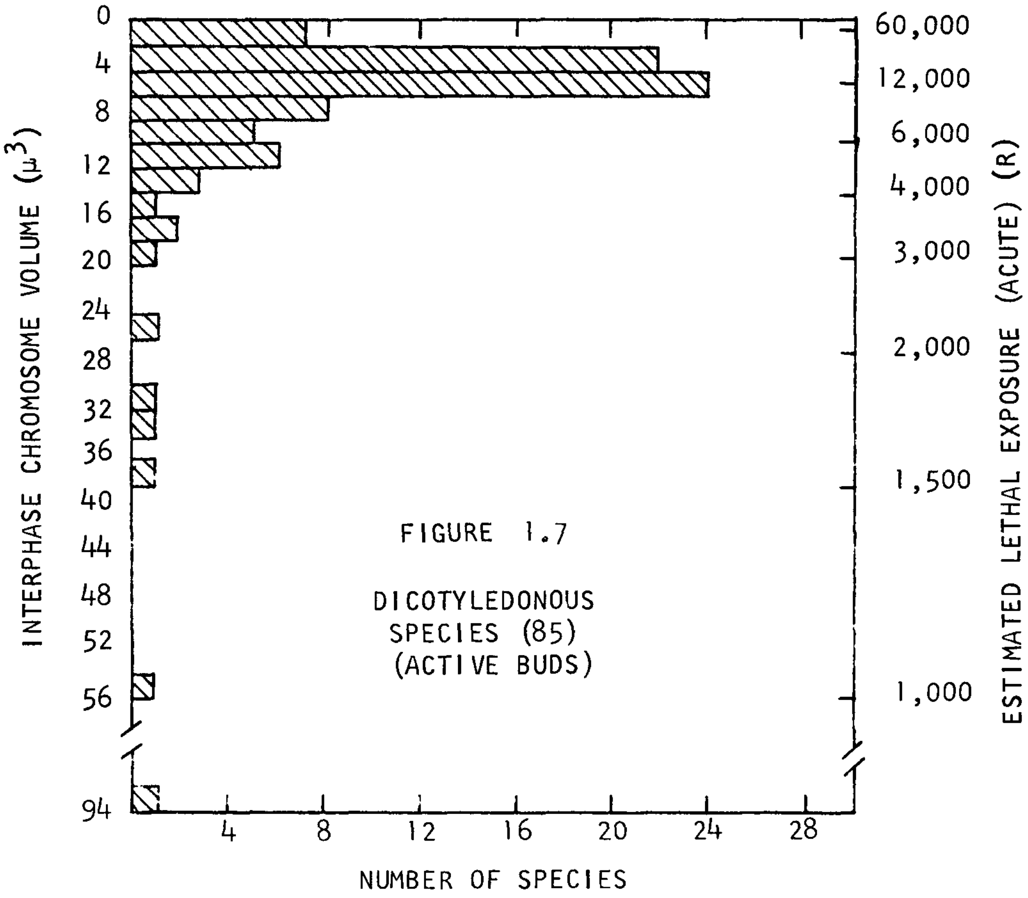


FIGURE 1.7

DICOTYLEDONOUS SPECIES (85) (ACTIVE BUDS)

2. Mitotic cycle (growth rate): Mitosis is the ordinary process of cell division involved in growth. The target-size theory is consistent with the hypothesis that the shorter the mitotic cycle--the less time between cell divisions--the smaller the probability of damage occurring during the interphase state (between successive reproductions) as a consequence of a constant level of exposure. This is especially relevant in considering the effects of low-level chronic radiation, where damage to the nucleus can be correlated in some sense to the amount of energy which has been absorbed by the nucleus during the interphase (quiescent) period. This hypothesis has been tested on *Pisum sativum* (green pea) by using temperature to control the duration of the mitotic cycle. It was found that the percentage of cells--observed just prior to splitting (anaphase)--having damaged chromosomes increased with cycle duration.[55] Thus, other things being equal, one would expect environmental factors which increase the rate of growth or of recovery to decrease the probability of damage. However, as a general rule, rapidly growing cells also have larger nuclei than dormant or slow-growing cells. This may provide an explanation for the otherwise contradictory empirical fact that rapidly growing cells are more (rather than less) radiosensitive than slow growing ones--which is the basis for the use of radiation to destroy rapidly growing cancer cells.[56]

In addition to the factors mentioned above, the "fine structure" of the nuclei may have some importance, e.g. the number and position of centromeres* on the chromosomes, the amount and distribution of heterochromatin,** etc. Similarly, the size and number of nucleoli (small granules inside the nucleus, whose function is imperfectly understood) seem to influence radiosensitivity slightly.[57] Variables not yet identified may also be found to affect the issue. However, evidence is accumulating that these factors *in toto* are of relatively minor significance compared to nuclear volume--DNA content and chromosome number.

The sensitivities of cells to other types of radiation which would be associated with fallout from nuclear detonations, have been studied far less extensively even than sensitivities to γ-rays.*** M. Heaslip has attempted to compare γ-sensitivity of various deciduous tree seeds

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*The centromeres are distinguishable during mitosis (when the daughter chromosomes--chromatids--migrate to opposite poles of the "spindle" during anaphase) as the parts which start first and lead the way.

**Chromatin is the chromosome-substance in the cell nucleus. It has two components: euchromatin ("true" chromatin) which apparently carries the genes, and heterochromatin, whose distinguishing characteristic is that of being easily stained and made visible under a microscope.

***Most experiments have actually used the γ-rays from Co-60 which is not present in appreciable amounts in fallout and whose energy spectrum is quite unlike the spectrum of average fallout.

with sensitivity to neutrons(from the Lockheed reactor), but no consistent pattern emerges from the preliminary data.[58] A more thoroughgoing test has been underway at Oak Ridge since 1963. It is safe to say that differences either way by a factor of 2 or 3 may be expected, probably depending fairly strongly on energy. As regards β-radiation, there has not been an adequate experimental test program, even though accelerators which could produce appropriate electron energies* are widely available.

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*For example the decay of Sr-90 and its daughter Y-90 produces 0.54 mev and 2.27 mev electrons, which could easily be simulated by a Van de Graaf accelerator.

3. Plants

It is important to note that the notion of radiosensitivity as applied to complex organisms is much less well-defined than as applied to individual cells. For example, the concept of "lethal dose" is somewhat ambiguous as applied to many kinds of adult plants, seeds, and even insects. In one experiment it was observed that irradiated powder-post beetles (Lyctus planicollis) revived after three days of apparent death, which posed difficult problems of judgment for the experimenters.[59] Trees defoliated as a result of long-term chronic doses of radiation and, apparently dead, have been known to show signs of life when the radiation source was removed. It is especially difficult to know the precise point at which an underground root system ceases to be capable of vegetative regeneration.* All attempts to tabulate data on plant radiosensitivities must be read and understood in the light of these difficulties (both for the experimenter and the tabulator). The graduated set of responses in Table 1-3 leans heavily on data compiled by Sparrow and Woodwell.[60]

Empirically, the rate at which the radiation is absorbed is sometimes very significant: for example, Sparrow and Woodwell noted that the lethal dose for Pinus strobus (eastern white pine), when subjected to an average of 20 roentgens per day for 15 months, was over 9,000 roentgens; while an acute exposure of only 600 roentgens was fatal for seedlings irradiated over a 16.5-hour period.[61] The computed LD_{100} for adult pine trees is about 1000 R (see Table 1-4). Similarly, in other cases there will be a greater or lesser difference between the acute and chronic lethal doses, depending on how fast growth and recovery processes take place. In the case of the pine tree more than 90% of the damage done by the low-level chronic radiation was presumably actually repaired in the period of the experiment. If repair mechanisms were faster, the difference between chronic and acute lethal doses would be greater still.

Since the accumulated total dose from fallout, after two weeks, exceeds 90% of the so-called "infinity-dose," in most instances it is probably reasonable to calculate responses as though most of the dose were instantaneous.** On the basis of direct observation, as well as predictions derived from measurements of chromosome number and nuclear volume, Table 1-4 summarizes the probable sensitivities to acute doses of radiation of many of the important plant species. The numerical values given have not in all cases been measured directly, but it is estimated to be 95% probable that the correct values lie within ± 25% of the predicted ones. The data is from Sparrow.[62]

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*Stumps of American chestnut trees "killed" by the chestnut blight 30 years ago sometimes still send up shoots--which are promptly blighted again. As a practical matter, of course, regeneration from root stock is essentially equivalent to regeneration from seed, i.e. a "new" plant is created.

**This approximation is less valid in the case of long-delayed fallout, where most of the radioactive decay has already occurred by the time it comes down. Such a situation would occur far downwind of a target.

Table 1-3

Levels of Symptomatic Response

Symptom	Radiation	Other Causes	Ref.
1. Mild growth stimulation	Observed in some cases, e.g. *Arenaria*	Observed in some cases, especially *pinus spp.*, after fire.	63
2. Mild growth inhibition early leaf fall; early cessation of flowering; 20-40% reduction in seed production.	10-20% of LD_{50}	Typical reaction to hot, dry spell or excessive cold.	64,65
3. Moderate growth inhibition 50% retarded leaf development;	20-50% of LD_{50}		65,66 67,68
apical buds do not develop but lateral buds (near trunk) do; 40-80% reduction in flower and seed development;		Typical symptom of shock following transplanting, or severe drought.	
noticeable (50-200%) increase in pest activity/reduced disease resistance.		Sometimes follows severe freeze (e.g. citrus trees) or drought.	
4. Severe inhibition	>50% of LD_{50}		
100% sterility; dormancy (cambium remains green but no leaves or buds);			64,65 66,67 69
discoloration and defoliation; deformities.		May follow fungal, bacterial or virus infection or poisoning.	
stem twisting (not a symptom of radiation).		Heat or drought.	

NOTE: The LD_{50} is about 75% of LD_{100}.

A fact which has only recently become apparent is that higher plants are typically several (e.g. 2-10) times less resistant to radiation administered in the open field than they are in a laboratory where they are protected from other environmental insults.[70] This lends support to the notion that radiation is only one of several stress factors, the synergistic combination of which is the significant parameter.

The vulnerability of plants to fallout radiation from a nuclear explosion depends on various factors in addition to γ-sensitivity. Some particles will adhere to foliage and some will drift down to the ground, but there are large variations as well as uncertainties as to how much of the total amount will do which. An isolated pine tree, for example, might intercept relatively few particles, due to the spare shape and low density of the needles. A beech tree in full leaf would probably intercept virtually all of the fallout (assuming a uniform vertical drift without much air turbulence), just as it intercepts practically all (99%) of the raindrops. The same tree in winter would intercept essentially none of either. Other plants would intercept different fractions under different circumstances.

The retention of fallout particles on foliage has been a subject of considerable controversy. British figures, based on data from the Windscale disaster, suggested high average retention ($\sim$ 25%) for small particles. U.S. data, based on Nevada experiments, suggested the reverse--practically no retention ($\sim$ .1%). Recent work in Costa Rica, using the volcanic ejecta as a fallout simulant, seems to tend to confirm the British results (although final reports are not yet available at this time).

These differences affect the actual absorbed γ-dose at the growing points (meristems). In the case of a tall tree, fallout adhering to leaves would result in a γ-dose rate 2 to 3 or more times greater than radiation originating at ground level, due to altered geometry as well as the shielding of air, branches, trunk and leaves. Furthermore, the effective β-dose due to fallout intercepted by the foliage might be very important. Other relevant factors include the following:

Large woody species (e.g. trees) are likely to be relatively less subject to damage from the β-component in fallout than smaller plants with more exposed meristems, due to the thickness of the protective outer layers of tissue.

Plants having large surface/volume ratios may be relatively more susceptible to β-damage. In particular, the cross-sectional area exposed to the zenith might be an important parameter. Thus spiky, narrow-leaved plants (e.g. grasses) offer less available surface than broad-leaved plants (e.g. members of the cabbage family). Thick-leaved plants may be less susceptible than thin-leaved plants. Downturned leaves or flowers are less likely to catch and hold fallout material than upturned ones.

Consequences of γ or β damage to herbaceous perennials would be temporary, since such plants die back to the ground each season anyway. Consequences to herbaceous annuals would be equally temporary, provided seed, labor, etc., were available for the following year's planting. In the case of woody perennials, damage would have more lasting results, depending on the rate of growth. Deciduous trees are mostly capable of vegetative reproduction from root stock, whereas evergreens do not normally regrow in this fashion. This could be an important distinction. All things considered, evergreens appear to be far more susceptible than other forms both to direct damage and (as will appear later) to secondary effects such as fire, disease and insect outbreaks.

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD_{100} for Acute γ-Radiation	Other Studies
Gymnosperms		
(Order Coniferae)		
Pinaceae (evergreens)	Very high γ-sensitivity; slow-growing woody perennials, no vegetative reproduction as a rule, spiky leaves (needles). Good shielding vs. β. Foliage year-round. Moderate to high interception of particles depending on species.	
Abies balsamea (balsam fir)	1,150 R	
Larix leptolepis (Japanese larch)	1,250 R	
Picea glauca (white spruce)	1,020 R	
Pinus strobus (eastern white pine)	1,000 R	71,72,73,74
Pinus rigida (pitch pine)	-	72,74,75,76 77,74,78,79,80
Pinus taeda (loblolly pine)	-	81,82,83,84
Cupressaceae[**]		
Thuja occidentalis (white cedar)	1,500 R	

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[*] Most experiments were done with γ-radiation from Co-60 unless otherwise specified.

[**] May be treated as sub-family of Pinaceae in some sources, but U.S.D.A. treats Cupressaceae as separate family.

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation (Cont.)

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD_{100} for Acute γ-Radiation	Other Studies
Gymnosperms		
(Order Coniferae, cont.)		
Taxaceae		
Taxus media Hatfieldi (yew)	800 R	85
Angiosperms		
(Subclass Monocotylae)		
Gramineae (grasses, cereals)	Cereals are annuals; range grasses are perennials capable of vegetative reproduction from roots. Low to moderate γ-sensitivity. Spiky leaves but no shielding vs. β. Low to moderate interception rate.	
Avena sativa (oats)	3,800 R	81
Hordeum vulgare (barley)	4,350 R	81,86
Oryza sativa (rice)	19,700 R	87
Secale cereale (rye)	4,350 R	81
Sorghum vulgare (sorghum)	7,600 R	81
Triticum aestivum (wheat)	4,000 R	81,88
Zea mays (corn)	4,200 R	71,81,89

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation (Cont.)

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD_{100} for Acute γ-Radiation	Other Studies
Angiosperms		
(Subclass *Dicotylae*)		
Leguminosae (legumes)	Mostly annuals. Low γ-sensitivity, low β-shielding, high interception in season.	
Glycine soja (soybean)	14,200 R	
Medicago sativa (alfalfa)	n.a.	81
Phaseolus vulgaris (kidney bean)	36,000 R	
Pisum sativum (garden pea)	4,600 R	90,91 92
Vicia faba (broadbean)	1,800 R	
Solanaceae (potato, tomato, tobacco)	Broad-leaved, non-woody annuals; low γ-sensitivity, low β-shielding, high interception in season.	
Lycopersicum esculentum (tomato)	12,400 R	81
Solanum tuberosum (potato)	12,600 R	93
Cruciferae (cabbage)	Same as above.	
Brassica oleracea capitata (cabbage)	12,300 R	

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation (Cont.)

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD_{100} for Acute γ-Radiation	Other Studies
Angiosperms		
(Subclass Dicotylae, cont.)		
Chenopodiaceae (beet, spinach)	Broad-leaved, non-woody annuals; low γ-sensitivity, low β-shielding, high interception in season.	
Beta vulgaris cicla (Swiss chard)	14,800 R	
Beta saccharifera (sugar beet)	13,400 R	81
Convolvulaceae	Same as above.	
Ipomoea batatas (sweet potato)	18,600 R	81
Cucurbitaceae (melon)	Same as above.	
Compositae (lettuce)	Same as above.	
Lactuca sativa (lettuce)	7,100 R	94
Umbelliferae (carrot, parsnip, celery)	Narrow-leaved, non-woody annuals; moderate β-interception, otherwise as above.	

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation (Cont.)

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD_{100} for Acute γ-Radiation	Other Studies
Angiosperms		
(Subclass *Dicotylae*, cont.)		
Liliaceae	Narrow-leaved, non-woody annuals; moderate β-interception, otherwise as above.	
Allium cepa (onion)	1,500 R	
Asparagus officinalis (asparagus)	8,600 R	81
Linaceae		
Linum usitatissimum (flax)	20,700 R	
Malvaceae		
Gossypium hirsutum (upland cotton)	10,100 R	81
Rosaceae (apple, plum, peach, berry)	Broad-leaved, woody perennials or trees, vegetative reproduction. γ-sensitivity unknown. Some β-shielding, high interception in season.	
Rutaceae, genus *Citrus*	Same as above except semi-tropical--hence foliage is year-round.	
Vitaceae (grapes)	Same as above.	

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation (Cont.)

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD$_{100}$ for Acute γ-Radiation	Other Studies
Angiosperms		
(Subclass Dicotylae, cont.)		
Betulaceae (birch, alder, hazel, willow)	Broad-leaved, soft wood perennials, vegetative reproduction. γ-sensitivity probably low; some β-shielding; high interception in season.	
Betula lutea (yellow birch)	8,000 R	
Aceraceae (maple)	Broad-leaved, hard wood perennials, otherwise as above.	
Acer saccharum (sugar maple)	8,000 R	80,95
Acer rubrum (red maple)	10,000 R	80,85,95
Fagaceae (oak, beech, chestnut)	Same as above	
Quercus rubra (red oak)	8,000 R	95,96
Q. alba (white oak)	-	71,74,78,80,95 96,97,98,99,100
Q. velutina (black oak)	-	77,80,101
Q. coccinea (scarlet oak)	-	74,77,102
Q. ilicifolia (bear oak)	-	74,77,97

Table 1-4

Vulnerability and Sensitivity of Important Plants to γ-Radiation (Cont.)

Family, Genus	Relevant Factors Affecting Over-all Vulnerability Including Approximate LD_{100} for Acute γ-Radiation	Other Studies
Angiosperms		
(Subclass *Dicotylae*, cont.)		
Juglondaceae (walnut, hickory)	Same as above	
Oleaceae		
Fraxinus americana (white ash)	10,000 R	80
Caprifoliaceae (honeysuckle)		
Sambucus canadensis (American elder)	2,000 R	

4. Insects

In the case of insects there is often a significant variation from one stage of the insect's life cycle to the next. During the stages when cells are rapidly differentiating, some insects seem to be sensitive to instantaneous doses of a few hundred roentgens or less. However, resistance increases very rapidly with maturity. Adult insects seem to be quite insensitive, on the whole, mainly because there is practically no cell replacement. Instantaneous doses are very much more effective than cumulative doses. Adult insects may, however, be sterilized by radiation as little as 10% of the lethal dose. The well-known use of sterilized males to eliminate the screwworm fly, Callitroga hominivorax, from Curacao[103] is a practical application of this fact. There is some slight evidence that insects may be at least as sensitive to β-radiation and several times more sensitive to neutrons (per unit energy) than to γ-radiation, as are higher animals. To the extent that they come directly in contact with fallout, β-radiation is likely to be much more important for insects than γ-radiation (the reverse of the situation for large animals), due to the fact that the surface β-dose is typically as much as forty times as great as the γ-dose. Insects with hairy bodies, such as bees, moths, butterflies, etc., may also be inclined to pick up some fallout particles, as they do pollen, and carry them around externally.

Some insects will also presumably ingest fallout in their food, but the amount will depend on their habits. Leaf chewers, such as grasshoppers, crickets, caterpillars, bean beetles, adult Japanese beetles, etc., are likely to be most subject to this hazard. Juice-sucking insects such as aphids, leafhoppers, and white flies may ingest less, due to discrimination factors in the plant. Burrowing insects, such as bark beetles, weevils, maggots, worms, etc., are probably safest from both external and internal β-doses. Predatory insects, such as praying mantis, lady beetles, etc., will receive external doses comparable to those of their prey and will ingest amounts proportional to the quantities retained in the tissues of the prey. Insects spending their larval period underground will get much smaller doses during this most sensitive stage of the life cycle.

The relatively sparse information currently available on sensitivities of insects to radiation is summarized in Table 1-5. A much more comprehensive survey is to be published in the near future by Gustafson.[104]

The over-all vulnerability of insects to radiation from fallout depends on other factors as well. In a given fallout field, different species will receive radically different actual doses because of wide variations in their morphology and life habits. Aphids, caterpillars, scale insects, leaf miners and leafhoppers feeding on leaves would probably receive substantial β-doses, for example, whereas grubs, weevils, borers and bark beetles would be relatively protected. Long legs or hard shells would also offer some protection from the short-range β-particles. Even the difference between the dose received on the top of a leaf versus the dose received on the underside could be significant.

Predaceous or parasitic insects such as dragonflies, May flies, aphidlions, lacewings, and lady beetles would probably be somewhat less subject, on the average, than most of their prey to direct external contact with β-emitters. (The situation as regards internal dosage is unclear, and depends on the operation of discrimination mechanisms in the metabolisms of their prey.)

Until more radiosensitivity data are available on insects it appears that insect populations will be comparatively vulnerable to sterilizing doses of β-radiation. The more protected species such as bark beetles are the least likely to suffer any ill effects.

Table I-5

Vulnerability and Sensitivity of Arthropods (Including Insects)

Order, Family	Relevant Factors Affecting Over-all Insect Vulnerability Including Specific Radiosensitivities
Class Arachnida	
Order Araneida (spiders)	Predaceous and omnivorous. Soft bodies.
Order Acarina (mites, ticks)	Adults usually parasitic upon other animals.
Class Hexapoda (Insecta)	
Order Orthoptera (grasshoppers, crickets, mantids, roaches)	
Family Locustidae (grasshoppers)	Winter passed in egg stage about 1/2-2 inches below soil surface. Large chromosome volumes.
Grasshopper eggs still in ovary[105]	350 R caused sterilization.
Family Blattidae	
Periplaneta americana (American cockroach)[106]	1,000 R (β) caused sterilization. The LD_{50} is below 40,000 R (β).
Order Odonata (dragonflies, damselflies)	Live 1-3 years beneath water as nymphs. Predaceous: adults eat flying insects such as mosquitoes, horseflies. Could accumulate substantial internal doses.
Order Homoptera	Feed on plant juices or tree sap.
Family Cicadellidae (leafhoppers)	Feed on underside of leaf. May deposit eggs inside leaf tissues. Possibly vulnerable to β's on foliage.
Family Aphidae (aphids)	Can reproduce parthenogenetically. Overwinter as fertilized eggs attached to plants. Vulnerable to β's.
Family Coccidae (scales, mealybugs)	

All of the above Hexapoda have simple or incomplete metamorphosis. The following members of the class have a more complex metamorphosis.

Table 1-5

Vulnerability and Sensitivity of Arthropods (Including Insects) (Cont.)

Order, Family	Relevant Factors Affecting Over-all Insect Vulnerability Including Specific Radiosensitivities
Class *Hexapoda*	
Order *Coleoptera* (beetles, weevils)	Larvae usually grubs or borers. Pupae often exposed on top of leaves. Do not have cocoons as moths do.
Family *Cucujidae* (flat bark beetles)	Live under bark. Feed on wood-boring insects or stored grains. Not vulnerable to β's due to protection.
Family *Coccinellidae* (lady beetles)	Predaceous: feed on aphids, scale insects. Possibility of accumulating internal dose sufficient to sterilize.
Family *Dermestidae*	Feed on dead animal matter such as furs, carpets, as well as stored meat and grains. Low vulnerability.
Dermestes spp. (larder beetles)[107]	Less than 64,000 R (γ) is LD_{100} for both larvae and adults, although larvae die more quickly than adults at lower doses.
Attagenus piceus (black carpet beetle)[108]	The LD_{100} for larvae is less than 16,000 (γ); however, 80 days elapsed before all were dead. The adult LD_{100} is less than 64,000 and is reached within 12 days. At 64,000 R, it takes 60 days for larvae to reach LD_{100}. Low vulnerability.
Family *Ptinidae* (including *Anobiidae*, *Bostrichidae*, and *Lyctidae*)	Most live within dry or slightly decaying vegetable or animal matter. Not serious pest problems.
Anobium punctatum (furniture beetle)[109]	γ-radiation caused beetle to lay sterile eggs after 800 R. 4,000 R killed new eggs, but mature eggs not killed until 32,000 R.
Xestobium rufovillosum (deathwatch beetle)[110]	Same as for *Anobium punctatum*.
Lyctus planicollis (powder-post beetle)[111]	Same as for *Anobium punctatum* eggs. 90% of the adults died within 7 days at 64,000 R.

Table 1-5

Vulnerability and Sensitivity of Arthropods (Including Insects)(Cont.)

Order, Family	Relevant Factors Affecting Over-all Insect Vulnerability Including Specific Radiosensitivities
Order Coleoptera (Cont.)	
Family Ptinidae (Cont.)	
Lasioderma serricorne (cigarette beetle)[112]	LD$_{100}$ from γ-radiation for adults is less than 16,000 R
Rhyzopertha spp. (lesser grain borer)[113]	6,000 R (γ) caused complete sterilization, but LD$_{100}$ for adults was only reached after 23 days at 64,000 R.
Family Elateridae (click beetles)	Larvae are tough-skinned wireworms which eat planted seeds and crop roots underground. Relatively invulnerable.
Family Tenebrionidae	Vegetarians. Often feed upon stored grains. Low vulnerability.
Tribolium confusorum (confused flour beetle)[114]	The sterilization dose is 4,000 R (γ). The LD$_{100}$ after 13 days is less than 16,000 for adults.
Tribolium castaneum (red flour beetle)[115]	The sterilization dose is 5,000 R for adults and 2,000 R for eggs. The adult LD$_{100}$ is 30,000 within 21-28 days.
Family Scarabaeidae (May beetles, Japanese beetles)	Grubs of Japanese beetles spend about 10 months in soil. Eat roots of crops and grasses. Adults eat foliage. Grubs & pupae well protected. Adults risk sterilization via internal dose.
Family Chrysomelidae (Colorado potato beetle, asparagus beetle, elm-leaf beetle, corn rootworms, cucumber beetles)	Some larvae eat roots or bore through stems and roots. Most adults eat foliage. Vulnerability low, as above.
Family Curculionidae (cotton boll weevil, clover-bud weevil, sweet-potato beetle)	Larvae feed within nuts, seeds, fruits, stems or roots. Vulnerability as above.
Sitophilus spp. (rice weevil)[116]	The sterilization dose is 6,000 R (γ), and the LD$_{100}$ after 12 days is about 16,000 for adults.
Family Scolytidae (bark beetles)	Most live under bark in all stages. Low vulnerability.

Table 1-5

Vulnerability and Sensitivity of Arthropods (Including Insects) (Cont.)

Order, Family	Relevant Factors Affecting Over-all Insect Vulnerabilities Including Specific Radiosensitivities
Class *Hexapoda*	
Order *Neuroptera* (lacewings, aphid-lions, brown lacewings)	Larvae predaceous on aphids, mealybugs, mites, etc. Possibility of ingesting dose sufficient to sterilize.
Order *Lepidoptera* (moths)	Larval stages usually leaf-eaters--caterpillars. Moth pupae wrapped in cocoons.
Family *Gelechiidae* (pink bollworm of cotton, potato tuberworm)	Larvae: some are leaf miners; others are leaf rollers or borers. Vulnerable to β's.
Family *Tortricidae* (spruce budworm)	Larvae feed within rolled leaves. β-vulnerability?
Family *Olethrentidae* (codling moth)	Larvae feed on foliage. Vulnerable to β's.
Family *Pyralididae* (European corn borer, cornstalk borers, melon worm)	Larvae feed in rolled leaves, as borers, or inside grain products. Possible β-vulnerability.
Family *Noctuidae* (cutworm moths, cotton leaf worm, corn earworm)	Some eat exposed on leaves; others, underground.
Order *Hymenoptera*	
Several families of sawflies (wheat stem sawfly, elm sawfly)	Eggs may be deposited in plant tissues. Larvae bore into stems of herbaceous plants. β-vulnerable as eggs?
Various families of parasitic wasps	Larvae of some families develop in or next to other insects, especially destructive grubs or caterpillars, who are plant pests. Other larvae develop in seeds or stems of herbaceous plants. Live in various kinds of nests: mud cells, burrows, paper.
Family *Braconidae*	
Bracon hebetor (parasitic wasp)[117]	5,000 R of X rays found to cause sterilization of females, but 7,500 R was needed to sterilize males. The LD_{50} for male sperm was 2,500 R No adults were killed even after doses as high as 180,000 R. Eggs vulnerable to β's?

Table 1-5

Vulnerability and Sensitivity of Arthropods (Including Insects)(Cont.)

Order, Family	Relevant Factors Affecting Over-all Insect Vulnerability Including Specific Radiosensitivities
Class *Hexapoda*	
Order *Hymenoptera* (Cont.)	
Various families of bees	Abundant hairs that aid in pollination would pick up radioactive debris. Eggs may be protected, however(?)
Order *Diptera* (flies, mosquitoes, gnats, midges)	Most larvae called maggots--live in water, mud, decaying animal matter or inside bodies of plants, insects or other animals.
Family *Culicidae* (mosquitoes)	
Culex fatigans[118]	The sterilization dose for mosquito eggs is 3,000 R (γ). Vulnerable to β's in surface fallout.
Family *Drosophilidae*	
Drosophila melanogaster (fruit fly)[119]	The LD$_{50}$ from X rays for eggs ranged from 170-200 R for 3-hr. eggs up to 810 r for 7.5-hr. eggs. Fast neutrons of 30 R killed 50% of the 3-hr. eggs. 2,800 R from X rays sterilized 50% of the pupae. The adult LD$_{100}$ from γ rays was less than 64,000 R over a period of 21 days to less than 193,000 in 2 days. β-radiation killed all of the adults who had not been fed at 60,000 R, but the same dosage only killed 60% when the adults had been fed.
Family *Calliphoridae*	
Callitroga hominivorax (screwworm fly)[120,121]	The sterilization dose from X-rays ranged from 2,500 R for male pupae to 5,000 R for female pupae. Pupae vulnerable to β-radiation on ground. Larvae probably not vulnerable to doses which would spare host.

5. Vertebrates

In the case of chronic radiation, life shortening can be predicted (in principle) by computing the cell replacement rates for various physiological functions, and the cell destruction rate due to the radiation. Since natural aging is presumably a function of the degree to which cell replacement fails to keep up with "demand," chronic irradiation can be thought of as an artificially stepped up aging process. These considerations have been used to predict effects on large mammals.[122] The somatic effects of radiation on humans, including life shortening, carcinogenesis, and genetic problems, have been discussed exhaustively elsewhere[123] and we shall not comment further on this matter.

Sensitivities of complex organisms to acute radiation are determined by the component cells in the organism which are most radiosensitive and slowest to reproduce among those types whose metabolic functions are critical and cannot be by-passed or dispensed with, even temporarily. Clearly the organism's capability for regenerating the damaged tissue must be taken into account, especially for chronic or sublethal doses. The most sensitive part of the human organism (in the above sense), and presumably of most other mammalian species, is the hematopoietic (blood-forming) tissue in the bone marrow, without which the organism soon loses its ability to defend itself against attacks by microbes.* Death resulting from "radiation disease" (of mammals) is usually due to a massive generalized parasitic infection of the whole body at once. However, in considering widely dissimilar organisms, e.g. plants, insects, invertebrates, etc., the mammalian example is not necessarily a good guide, and the proximate cause of radiation death is likely to vary from order to order, if not from species to species. To date, many of these detailed mechanisms have not been thoroughly studied.

In passing, we should point out that there are some factors which can apparently alter the degree of susceptibility in mammals. The oxygen level in the blood stream seems to be important. This suggests that a lowered rate of metabolism (e.g., lowered body temperature) could offer some protection. Considerable research is now in progress to determine whether susceptibility can be substantially reduced by means of various chemicals.[124] Several thousand compounds have been tested in a major government-sponsored effort directed by Walter Reed Army Institute of Research. The heterocyclic mercaptoamines, particularly β-mercaptoethylamine, appeared most effective. Twofold or threefold protection without "undue" toxicity has been demonstrated with laboratory animals, but only under carefully controlled conditions. Moreover, some post-exposure treatment is also reportedly beneficial where pre-exposure protection has been given, especially at higher levels of irradiation.[125] None of the known treatments is particularly promising for application to humans, at present writing.

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*The epithelial cells lining the intestines are the next most sensitive group.

Curiously enough there is some surprising evidence of a substantial difference in radiosensitivity between morning and night (for laboratory rats anesthetized with sodium pentobarbital). Twenty animals (in four different groups) given 900 roentgens at 9 p.m. all died within 13 days, whereas twenty animals in four groups given the same dose at 9 a.m. were all still alive and apparently healthy 130 days later. The experiments have not been confirmed elsewhere to the author's knowledge, and their significance is therefore questionable.[126]

One other result which is apparently well established although of doubtful importance, is the fact that animals raised in germ-free environments are substantially less susceptible to radiation than animals *in vivo*. Typically the LD_{50} for germ-free animals is $\sim$ 10% higher than the LD_{50} for their contaminated brethren.[127]

Table 1-6

Radiation Sensitivity of Higher Vertebrates to Acute γ Doses[128,129,130]

Species	LD_{50}/30 Days	
	Air Dose (R)	Absorbed Dose (rads) at Midcenter
Class *Amphibia*		
Order *Anura*		
Family *Ranidae*		
Rana spp. (frog)	-	700
Order *Urodela*		
Family *Salmandridae*		
Triturus spp. (newt)	-	3000
Class *Reptilia*		
Order *Chelonia*		
Family *Testudinidae*		
Testudo spp. (tortoise)	-	1500
Class *Aves*		
Order *Columiformes*		
Family *Columbidae*		
Columba spp. (pigeon)	920 ± 160	-
Order *Passeriformes*		
Family *Ploceidae* (African weaver finch)	1060 ± 100	-
Order *Psittaciformes*		
Family *Conuropsis*		
Conuropsis carolinensis (parakeet)	1800 ± 75	-
Order *Galliformes*		
Family *Phasianidae*		
Gallus domesticus (chicken)	600 (males) 1000 (females)	700 ± 100

Class Mammalia		
Order Carnivora		
Family Canidae		
Canis familiaris (dog)	280	250
Order Rodentia		
Family Cricetidae		
Microtus spp. (mouse)	440	640 (705 germ-free)
Family Caviidae		
Cavia porcellus (guinea pig)	340	450
Family Muridae		
Rattus spp. (rat)	640	714
Order Lagomorpha		
Family Leporidae		
Oryctolagus cuniculus (rabbit)	800	750
Order Primates		
Family Cebidae		
Cebus spp. (monkey)	760	550-600
Family Hominidae		
Homo sapiens (man)	450 ?	300?
Order Artiodactyla		
Family Bovidae (Ruminantia)		
Bos taurus (cattle)	540 ± 25	-
Ovis spp. (sheep)	520	200
Capra spp. (goat)	350	240
Family Suidae		
Sus spp. (swine)	600+80 (γ) 490 ± 10 (γ+n)	250
Order Perissodactyla		
Family Equidae		
Equus asinus (burro)	650 +30	255 (γ) 375 (γ+n)

The absorbed dose at midcenter may be taken as representative of the dose received by all body tissues. For large animals, the midcenter dose is smaller than the air dose, due to scattering and shielding by the outer parts of the body. Near the surface, on the other hand, only the backscatter is significant and the absorbed dose tends to be slightly larger than the air dose. In the case of smaller animals, the latter phenomenon results in the absorbed dose at midcenter being greater than the air dose. In a few cases where doses have been given from sources with quite different energy characteristics (e.g., X-rays, 0.75 Mev γ's, 1.25 Mev γ's, etc.), fairly wide variations have been noted in sensitivities (± 20%).

6. Radio-nuclide Cycling

The cycling process which leads to the appearance of Sr-90 and Cs-137 in human diets has been investigated under the stimulus of public concern about atmospheric testing of nuclear weapons.[131] Our present focus of interest is, of course, on much higher levels of contamination, such as might follow a nuclear war.

The importance of Sr-90 stems from its long physical half-life (27.7 years) and the long biological residence time of the fraction which is incorporated in new bone. As Table 1-1 shows, it is a β-emitter which means the radiation is not penetrating. However, Sr-90 is chemically similar to calcium, and some of it becomes incorporated in permanent bone structure. Hence the Sr-90 tends to concentrate just where it can do most damage to bome marrow where the blood-forming (hematopoietic) cells are located.

As stated earlier, contamination of edible plant parts may be of two kinds: (a) foliar retention and absorbtion and (b) uptake via roots. The magnitude of the foliar contribution depends on:

1. The rate of deposition of particles of world-wide fallout ($\lesssim 25\mu$ radii) which come down over a period of years.
2. The fractional retention of fallout by foliage.
3. The "initial" solubility of the Sr-90 atoms in the fallout, i.e. the fraction which will dissolve during the retention time.
4. The rate of direct absorbtion into the leaves, which appears to vary somewhat according to the concentration of chemically similar atoms in the soil. Thus Sr-90 will be absorbed less readily if the soil is calcium-rich, and vice versa.
5. The internal metabolic transfer of contaminants, e.g., from leaves of stems to fruit or seeds.
6. Amount remaining externally on edible portions--not translocated.

Uptake from soil via roots is related to the following:

1. Sr-90/Ca ratio and absolute Ca availability in the soil. Sr-90 is taken up very readily where soil Ca is low, less so where Ca is adequate.
2. The long-term solubility of the Sr-90 atoms on the fallout particles. Sr-90 actually incorporated into the glassy silica-alumina-iron matrix of condensed liquid soil will probably be unavailable during the time spans of interest except where weathering is extreme, as in stream beds. Ion-exchange interactions in the soil may also tie up some of the Sr-90 in insoluble form.
3. Internal transfer. Some plant parts accumulate calcium (and hence Sr-90) while others do not.

The rate of fallout deposition is determined by the residence time of dust in the stratosphere. On the basis of atmospheric sampling studies conducted by Isotopes Inc. and the Defense Atomic Support Agency (DASA), the half removal times for radioactive debris in the stratosphere range up to about 60 months for the highest layers (above 45 km.).[132] The rate of fallout deposition decreases by a factor of roughly 2 each year. After 5 years, the amount deposited in a year would be only about 1% of the amount already accumulated. Three-fourths of the fallout is deposited in the hemisphere where it originated (presumably the northern), and about one-fourth in the temperate (high rainfall) zones between 30° and 45° N. latitude--which includes the N-S limits of the CONUS. Thus roughly 2.5% of the total world-wide fallout would be expected to descend inside the United States at an average rate beginning at about 1% per year and dropping by a factor of 2 or so each succeeding year. The fraction of Sr-90 in world-wide fallout would be, according to previous assumptions, about 50% of the total amount produced, or 50,000 curies per MT (fission). A war involving 20,000 (fission) MT's on both sides would inject 10^9 curies of Sr-90 into the stratosphere, of which around 10^7 curies would descend on CONUS in the first year and decreasing amounts each successive year. This amounts to 3.3 C/mi^2 the first year at a location with average rainfall.

The fractional retention on pasture has been estimated[133] to be on the order of 25%, depending on detail on the plant configuration and particle size.* Smaller particles (coming down later) would be retained longer, hence the contributions from the 2nd, 3rd, and 4th years might still contribute non-negligible fractions of the first year amount. Initial solubility (i.e., within the residence time on foliage) is estimated by Russell and Burton to be 50% for delayed fallout.[134] Thus over-all availability, the product of retention and solubility, would be something like 12.5%.

Miller has made some preliminary attempts to devise empirical-phenomenological models handling all of these variables. Some worthwhile results have been obtained, although the calculations are lengthy and require the use of computers.[135]

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*Since most late fallout comes down in conjunction with rainfall, the fraction retained on the foliage would seem, as a first approximation, to be roughly equal to the fraction of total precipitation which remains on leaf surfaces and is either absorbed directly or evaporates. The fractional retention may be increased in some instances where leaf surfaces are especially adapted to trapping small particles (e.g., by means of fine hairs) but this mechanism seems likely to be of secondary importance. Light precipitation in the form of fog, mist or drizzle may simply wet the surface of leaves and stems, whereas heavier rainfall (or snowfall) mostly reaches the ground and either soaks in or runs off the surface. There are wide variations in type of precipitation from place to place, and retention on foliage may vary over most of the range between zero and a hundred per cent. The 25% figure quoted cannot be safely generalized, since it is hard to see how to arrive at a meaningful "average" over the different possibilities. See also discussion in section 1 of this chapter.

A less ambitious method of correlating past experience of Sr-90 contamination of foodstuffs (due to nuclear weapons testing) to hypothetical future situations is to use an empirical formula to correlate observed concentrations $Q^{(k)}$ of a food (k) with the observed rate F_r and cumulative total deposition in the soil F_c

$$Q^{(k)} = A^{(k)}F_r + B^{(k)}F_c$$

where $A^{(k)}$, $B^{(k)}$ are coefficients which are deduced by fitting the above in a rather ad hoc manner to the statistical data. The product AF_r represents the contribution due to direct contamination of foliage. BF_c represents the uptake from the soil. Determinations of A, B have been made by Knapp;[136] Burton, Milbourn & Russell;[137] Kulp and Schulert;[138] and by the Reports of the U.N. Scientific Committee (1962 and 1964). The last two studies apparently supercede the earlier ones. For ease of comparison, we express both sets of results in familiar units: F_r is measured in mC/mi^2/year, F_c is in mC/mi^2, and Q is measured in strontium units (s.u. = $\mu\mu$C of Sr-90 per gram of calcium).

Table 1-7

Sr-90 Contamination of Various Foods*

	Rate Factor (A) (s.u./mC/mi^2/yr)	Cumulative Factor (B) (s.u./mC/mi^2)
Milk:		
U.S.A.	0.25	0.097
U.K.	0.32	0.075
Value adopted	0.29	0.11
Green vegetables	~0.4	~0.4
Root crops	0.0	~0.4
Cereals (unmilled)	7.2	~0.2
Cereals (milled)	2.5	~0.2

The coefficient for meat (muscular tissue) is not normally measured but assuming the animal's diet consists largely of green vegetation, a metabolic discrimination factor of at least 4 can be assumed[139] which would suggest

$$B^{(\text{meat})} \leq 0.1$$

To convert from a calculation of contamination level, in terms of strontium units, to dietary intake of Sr-90 the fractional contribution of each category of food (measured in Calories or some other appropriate way) must be multiplied by the ratio of calcium content to energy value (Calcium in mg/Cal.) or an equivalent measure.

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*Values in the original (U.N. report) are given in units of square kilometers instead of square miles. Values adopted were based partly on data for countries other than the U.S. and U.K.

Table 1-8

Sources of Dietary Calcium[140]

Food	Calcium (mg)/Cal.
Whole milk	1.75
Green vegetables	~3.5
Root crops	0.25 - 1.0
Cereals	~0.1
Meat	~0.04

Assessments of the Sr-90 problem to date have largely concluded that the major contribution to dietary contamination is from foliar uptake, which is proportional, as has been pointed out, to the rate of deposition. One piece of evidence in support of this is the fact that the coefficient A is, in most cases, considerably (e.g., five times) larger than the coefficient B (see Table 1-7),

If all weapons were detonated in the atmosphere this conclusion might well be valid for nuclear attack also. However, in the event of an attack involving a large number of groundbursts, the relative importance of the "cumulative" contribution would be increased, compared to the "rate" term, because of widespread distribution of local fallout.

It has sometimes apparently been assumed that Sr-90 in local fallout would be largely insoluble and therefore unavailable to plants. The solubility question has been discussed previously and it was concluded that beyond the 1000 R/hr (at 1 hr) isodose contour there might be an upper limit of about

$$\frac{88\ \text{C/mi}^2\ \text{soluble Sr-90}}{\text{KT/mi}^2}$$

in the local fallout region outside of the blast area. Assuming a 50-50 division of Sr-90 activity between local and world-wide fallout, practically all the Sr-90 eventually deposited on the CONUS would be attributable to the former, the world-wide component being diluted by being spread over much of the Northern Hemisphere. Assuming one-fourth of the world-wide total falls in the north temperate zone (between 30° and 45° N. latitude), a little arithmetic shows that the relative dilution would be about 1:50, assuming equal availability to plants.*

For a groundburst attack, then, a 5 to 1 intrinsic ratio favoring $A^{(k)}$ over $B^{(k)}$ is compensated by the 1 to 50 ratio in favor of the fallout of local origin, which comes down within a few hours and therefore contributes primarily via the soil uptake route. Hence we conclude that the coefficients $A^{(k)}$ and $B^{(k)}$ are not equally important, but that the latter dominate.

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*Thus a 50% long-term solubility in the local-fallout region where absorbtion is via roots would be equivalent to a 50% short-term solubility for delayed fallout, which is absorbed through foliage.

If all dietary calcium were obtained through food the safest sources would be animal products such as meat and milk. In view of the further consideration that it is apparently both feasible and relatively inexpensive to remove 90-95% of the Sr-90 from liquid milk, the advantages are even clearer. Ideally in a postattack environment one might wish to devise a diet containing as little natural calcium as possible (except from milk) and to provide as much purified supplementary mineral calcium as possible. These points are discussed at greater length in Chapter VIII.

An attack resulting in 1 KT/mi^2 (fission products) averaged over a given area would result in $\sim$ 90 C/mi^2 of "available" Sr-90 for the soil uptake route and perhaps 2 C/mi^2 of "available" Sr-90 for the foliar uptake route. Since the coefficients in the latter case are higher, this would be equivalent to $\sim$ 10 C/mi^2 by the soil uptake route. Milk produced by cows grazing in such an area would be contaminated on the average to a level of about 10,000 s.u.: grain would be twice as heavily contaminated, root crops and vegetables four times. The average for a mixed U.S.-type diet in which more than 50% of the calcium comes from milk might be 15,000 to 18,000 s.u.

The danger of ingestion of Sr-90 arises primarily from its bone-seeking characteristics. In the case of a single dose, perhaps less than 3% of the isotope taken into the body of an adult would become permanently incorporated into the bones, the rest being excreted over a period ranging from weeks to a few years. The percentage retained would, of course, be higher for children. However, if the diet should contain the same proportion of Sr-90 year after year, the amount in the skeleton would gradually build up toward an equilibrium level. The actual biological discrimination factor against Sr-90 in favor of calcium cuts the fraction retained to at most 20 or 25% of the fraction in the diet. Thus infants brought up on a postattack diet containing 15,000 s.u. of Sr-90 might be found to have a maximum of about 3,000 s.u. in their bones. The percentage retained in older children or adults would be smaller, depending on the age at the time of ingestion.

Assuming the Sr-90 is uniformly distributed in the skeleton, the initial (equilibrium) annual effective dose (in rem) for each thousand s.u. would be roughly as follows.[141]

compact bone:	2.7
spongious bone:	0.9
"average" bone:	2.5
"average" marrow*:	1.0

Dose rates in some skeletal regions would be higher due to non-uniformities of various kinds. An initial level of 1 KT/mi^2, leading to around 3,000 s.u. in new bone would result in a dose rate in the marrow cavity of the order of 3 rem per year.

To estimate lifetime dose one must allow for the spontaneous radioactive decay of the nuclide by about 2.5% per year, for the gradual loss of

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*This is strongly dependent on cavity size and configuration, as well as non-uniformities in calcium deposits, etc. Local regions of much higher dose rates are to be expected.

Sr-90 from the external (soil) reservoir--after any artificial decontamination--due to leaching and uptake by plants, and for gradual elimination from the body. Assuming the external "reservoir" of Sr-90 is depleted by 1 or 2% per year, there is probably enough metabolic turnover, due to exchange processes and bone resorption (1-10%), to maintain the equilibrium (once established, e.g., in infants born after the attack), between internal and external environments.[142] Taking into account the other two processes, one would expect an annual decrement (in the range) of 3.5-4.5%. For convenience we assume 4%. The total dose over a 70-year period would therefore be given by the initial annual dose rate multiplied by the factor*

$$\frac{1}{.04}\left[1 - \exp(-2.8)\right] \cong 23.5$$

In the standard case (3000 s.u. => 3 rem/year initial bone marrow dose rate), the total lifetime dose would therefore be ~ 70 rem. Summarizing the entire chain of derivations up to this point, we have:

1 KT/mi^2 (fission products)

=> 80 C/mi^2 soluble Sr-90
=> 15,000 s.u. in average (U.S.) diet
=> 3,000 s.u. in new bone
=> 3 rem/year mean initial equilibrium bone marrow dose
=> 70 rem mean lifetime bone marrow dose

The degree risk from bone cancer, leukemia, aplastic anemia and other known hazards is still a subject of controversy. The 1958 U.N. report[143] offers the figure of 1.5 cases of leukemia per year per million population per rem (in bone marrow) from a single exposure, or 22 deaths spread over 15 years (considered the period of risk). Assuming the risk from repeated exposures is cumulative with a linear dose-incidence relationship, and allowing for the above-mentioned exponential decay, the leukemogenetic rate for individuals born after the attack would presumably be in the neighborhood of 1150 per million of population.

An alternative hypothesis also discussed in the (1958) U.N. study is that leukemia might result if the total lifetime dose exceeded a threshold of 400 rem** at any point in the bone marrow. Owing to irregularities and non-uniformities, it was estimated that the maximum dose rate would be roughly five times the mean rate, or 5 rem per thousand s.u. Assuming a mean contamination level of 3,000 s.u. for new bone as above, the maximum lifetime (70 years) dose would be over 350 rem, corresponding to a mean bone-marrow dose of 70 rem. On the basis of this model, the only persons who would

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*Obtained by integrating an exponential function over the range 0-70 years.

**One can argue that this figure is much too low. A number of individuals have certainly survived accidental acute doses of 400 rem or more, (confined, perhaps, to an isolated part of the body) without contracting leukemia or cancer. Chronic doses are known to be much less effective in inducing cancer than acute doses. The 1962 and 1964 U.N. reports do not confirm (nor repudiate) the figure. Certainly one cannot put much trust in it.

eventually contract leukemia would be those who ingested more than 150% of the quantity of Sr-90 found in the average diet, but presumably more than 0.1% of the population would be in this group.

The two hypotheses evidently lead to startlingly different projections. There is relatively little solid experimental evidence on which to base a choice between the two, or, indeed, any other model permitting extrapolation to high levels of contamination. On theoretical grounds, however, it is worth remarking that the two divergent hypotheses can be treated essentially as special cases of a more general model in which susceptibility to leukemia, thought of as a variable characteristic of the human population, is assumed to have some intermediate distribution. Mortality is then the sum of all fractions of the population, susceptible to doses less than or equal to D. The linear dose-incidence function corresponds to a flat (i.e. constant) susceptibility distribution: for a lifetime dose between D and D + δD a fraction ϵ of the population contracts leukemia, where ϵ is constant (independent of D). The threshold model implies a step-function dose-incidence curve: for a lifetime dose less than D_o nobody contracts the disease, while above this level 100% of the population contracts it. The susceptibility distribution implied in this case is the so-called "delta-function," namely a function which is zero everywhere except at one point (D_o) where it is infinite, but in such a way that its integral is unity.

In fact, a more reasonable assumption than either of the foregoing is that the susceptibilities of the population (as a function of lifetime maximum bone marrow dose) are distributed according to a log-normal form:*

$$S(D)dD = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2\sigma^2} (\ln D/D_o)^2\right] d \ln D$$

where D_o is the center of the distribution (presumably numerically equal to about 400 rem maximum or 80 rem mean lifetime bone marrow dose) and σ is an undetermined parameter characteristic of the population. The integral:

$$\int_0^\infty S(D)dD = 1$$

independent of the value of σ. In the limit $\sigma \longrightarrow o$ it is easily verified that S(D) is mathematically equivalent to a delta-function centered at $D = D_o$, whence we obtain the "threshold" model as one limiting case. In the other extreme case, $\sigma \longrightarrow \infty$, it can be seen that S(D) becomes flatter and flatter, gradually approaching an (infinitesimal) constant value everywhere. This corresponds to a linear mortality function with an infinitesimal slope. A finite slope is obtained by chopping off the distribution at some finite upper limit (see Figures 1.8 and 1.9).

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*The so-called "normal" or Gaussian distribution is the most natural one to assume, in the absence of contradictory data, because it is so widespread in nature. For example, the distribution of "IQ's" in a population conforms fairly closely to this rule. We have no positive evidence for assuming it in the present case, however.

FIGURE 1.8

SUSCEPTIBILITY VS. DOSE

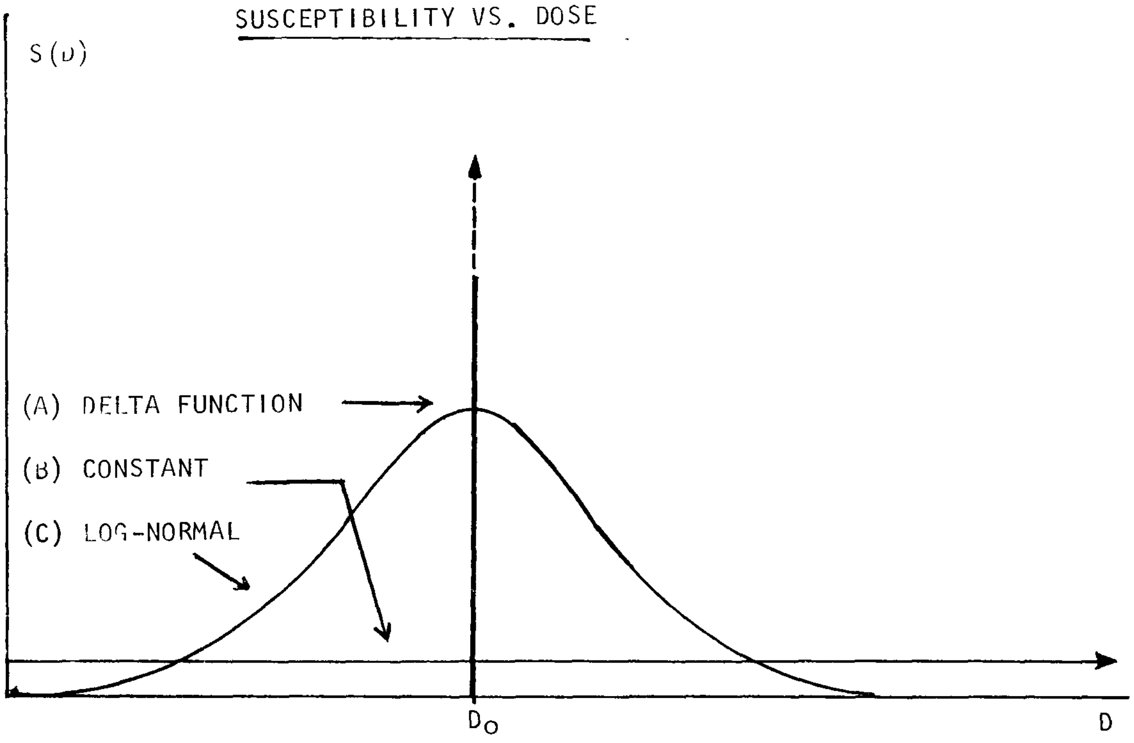
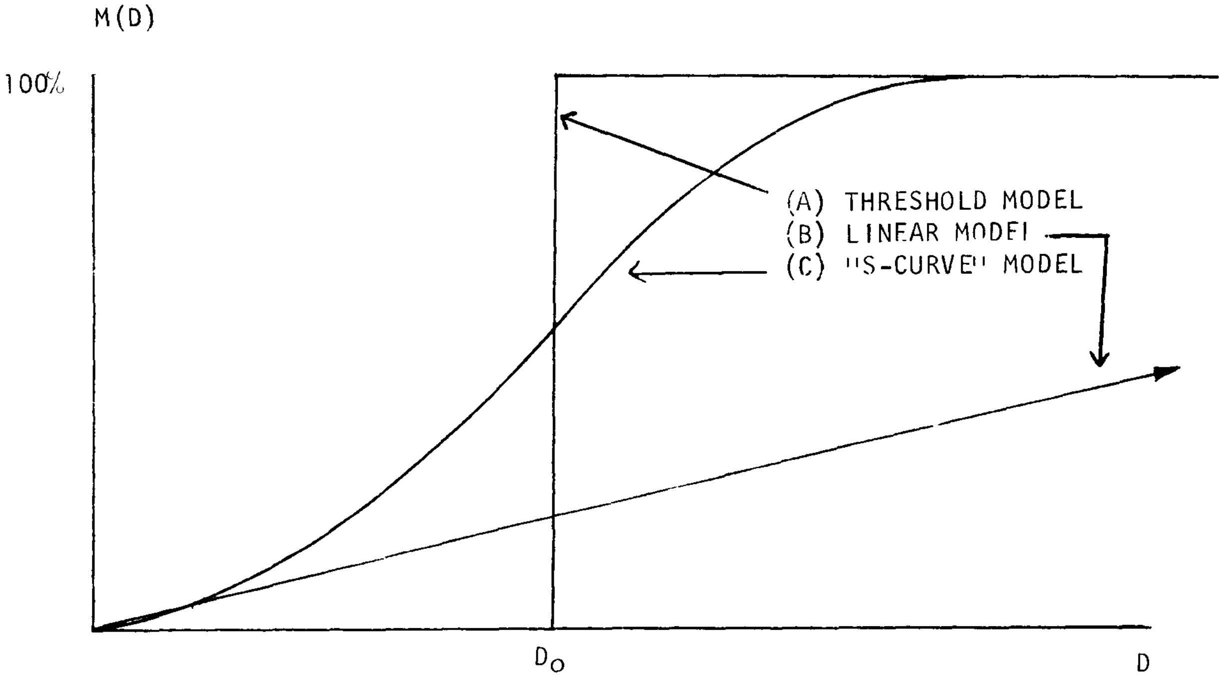


FIGURE 1.9

MORTALITY VS. DOSE



One can fix the parameter σ by insisting that the mortality $M(D)$ as given by the integrated "log-normal" model be equal to the mortality for some dose D where it can be inferred from empirical data, i.e. for $D = 1$ rem, let $M(D) = 20$ deaths per million or 2×10^{-5}.

Integrating the log-normal distribution postulated previously, one obtains:

$$M(D) = \int_0^D S(D')dD' = \tfrac{1}{2}\left[1-\mathrm{erf}\left(\frac{1}{\sigma\sqrt{2}}\ \ln\frac{D_o}{D}\right)\right] \qquad D < D_o$$

$$= \tfrac{1}{2}\left[1+\mathrm{erf}\left(\frac{1}{\sigma\sqrt{2}}\ \ln\frac{D}{D_o}\right)\right] \qquad D > D_o$$

Plotting this function (for particular choices of σ, D_o) it can be seen that the result is qualitatively similar to the familiar "S-curve" which typically describes the lethal effects of external radiation (or, for that matter, other toxic substances) on a population.* The chosen criterion for fixing σ requires that

$$\tfrac{1}{2}\left[1-\mathrm{erf}\left(\frac{1}{\sigma\sqrt{2}}\ \ln D_o\right)\right] = 2 \times 10^{-5}$$

whence

$$\frac{1}{\sigma\sqrt{2}}\ \ln D_o = \mathrm{erf}^{-1}(.99996) = 2.905$$

Using the log-normal distribution, with the above expression as a definition for σ, the mortality, within 70 years, due to leukemia and related disorders, resulting from a mean contamination level of 3,000 s.u. in bone, would be,

$$M(D) = \frac{1}{2}\left\{1 - \mathrm{erf}\left[2.905\left(1 - \frac{\ln D}{\ln D_o}\right)\right]\right\} \qquad D < D_o$$

$$= \frac{1}{2}\left\{1 + \mathrm{erf}\left[2.905\left(\frac{\ln D}{\ln D_o} - 1\right)\right]\right\} \qquad D > D_o$$

At the "standard" level of contamination (1 KT/mi^2) corresponding to a mean life-time bone marrow dose $D = 70$ rem, the foregoing suggests a rather wide range of values for the mortality $M(D)$, depending on one's choice of D_o, as shown in Figure 1.10. As indicated in a previous footnote, we consider the value of D_o proposed in the 1958 U.N. Report to be unreasonably low, resulting in an exaggerated mortality prediction. On the other hand, Figure 1.10 also suggests that mortality might still be fairly significant even if D_o were assumed to be a factor of 5 larger. It must be remembered, of course, that most of the deaths would occur in later years as the cumulative dose built up slowly, allowing for the possibility of medical breakthroughs which might conceivably alleviate the problem or even eliminate it altogether. (Several research centers are reportedly already testing leukemia vaccines, on a limited scale, on human patients. This or some other, e.g., chemotherapeutic, treatment may become available within the next decade.)

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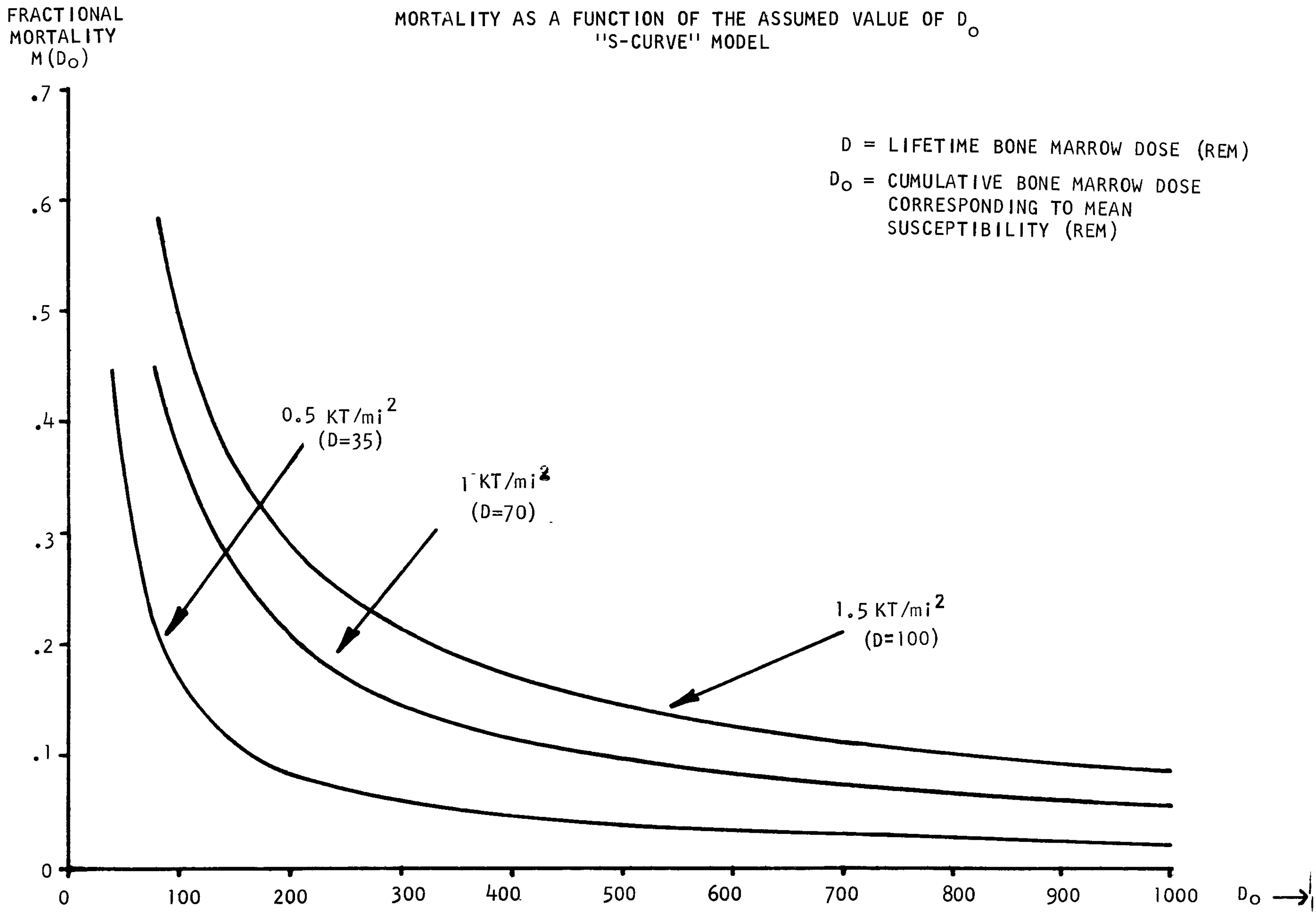
*The interpretation of an S-curve as an integrated susceptibility distribution goes back at least to 1926.[144]

FIGURE 1.10

MORTALITY AS A FUNCTION OF THE ASSUMED VALUE OF D_o
"S-CURVE" MODEL



The above model contains far too many uncertainties to be used for predictive purposes at this stage. It is, as pointed out above, rather sensitive to the assumed value of D_o, for which there seems to be a paucity of evidence. Its most fundamental assumption, which is certainly open to serious question, is that leukemogenesis and carcinogenesis can be described in terms of greater or lesser individual susceptibility (or resistance) to a causative agent which is essentially always present, e.g. a virus. The role of radiation would presumably be to reduce the body's natural resistance. The alternative view, on which any serious justification of the linear dose-incidence relationship would probably have to be based, is that the actual causative mechanism is a "rare" one--perhaps analogous to a mutation--whose intrinsic probability is strictly proportional to an intermediate cause such as the ionization caused by radiation.

This argument is properly one for specialists and we would merely point out that (apart from its quantitative aspects) the "log-normal" model is heuristically the most satisfactory of the three so far proposed, and does least violence, in some sense, to one's intuitive expectations. Further studies in this area would seem to be essential to reduce the contradictions and uncertainties which currently prevail.

The other important long-lived radioisotope in fallout is the γ-emitter Cs-137 (with a half-life of ~30 years). Assuming the ratio of Cs-137 to Sr-90 in local fallout is similar to that in world-wide fallout, namely, about 1.7 (although considerable local variation would be expected)[145] and that the ratio of solubilities of local to world-wide fallout would be the same in the two cases, a uniform deposition of 1 KT/mi^2 fission products would involve the equivalent of about 135 Curies of Cs-137 per square mile.

The body burden of Cs-137 reaches equilibrium relatively quickly because the metabolic half-life is comparatively short (~ 100 days). Hence persons of all ages would be affected roughly equally.* The following empirical relation seems to fit the known data reasonably well:[146]

$$Q = AF_r + BF_c$$

where, again, AF_r represents the contribution from direct contamination of foliage and BF_c, the contribution from the soil. Q has units of μμC of Cs-137 per gram of potassium (K) in the body (which, by analogy, might be called cesium units, or c.u.); F_r is measured in mC/mi^2/year; F_c in mC/mi^2 accumulated over the previous two years. The coefficients A,B have been determined roughly as follows:**[147]

$$A = 0.7 \pm 0.2 \ \frac{\mu\mu C \text{ of Cs-137/g(K)}}{mC/mi^2/yr.}$$

$$B = 1.1 \pm 0.3 \ \frac{\mu\mu C \text{ of Cs-137/g(K)}}{mC/mi^2}$$

---

*Actually, in proportion to body weight.

**Again, converting from km^2 to mi^2.

For local fallout, again, the cumulative contribution vastly outweighs the rate term, which may be neglected henceforth. For the "standard" case (1 KT/mi^2) one obtains, assuming an initial postattack value of F_c equal to 135 C of Cs-137 per square mile as above,

$$Q \cong 1.5 \times 10^5 \text{ c.u.}$$

The effective γ-dose has been given as follows:[148]

0.044 m rem/year per c.u. to bone cells
0.036 m rem/year per c.u. to cells lining bone surfaces
0.026 m rem/year per c.u. to bone marrow

In the 1964 U.N. Report it has been stated that these figures are probably a factor of 2.2 too high, due to the assumption in the 1962 Report, not confirmed in later studies, that Cs-137 is preferentially concentrated to some extent in bones and bone marrow. Allowing for this reduction, the initial mean dose rate resulting from a concentration of 1.5×10^5 c.u. would be about 3 rem/year to bone and 1.8 rem/year to marrow--which is comparable to or larger than the initial Sr-90 dose rate.

As time goes on, the ratio drops rapidly, however, because cesium apparently becomes unavailable to plants at a much faster rate than strontium, e.g., after three years the proportional rate of uptake from soil of cesium as compared to strontium drops from an initial value of 1/10* to 1/25.[149] Obviously, the lifetime cumulative dose from Cs-137 tends to be a smaller multiple of the initial dose rate, perhaps 3 compared to 23 for Sr-90. As regards carcinogenesis and leukenogenesis, the discrepancy is still greater because the cesium dose, due to penetrating γ-rays, is likely to be more uniform throughout the body than the strontium dose. Hence the factor of 5 between "mean" bone marrow dose and "peak" bone marrow dose would not apply to the cesium case. Because of all these factors, present indications are that Cs-137 probably is at least an order of magnitude less hazardous, in the long run, than Sr-90. This conclusion is, of course, valid only to the extent that the various links in the chain of argument are correct. Since many of them are still quite tentative, Cs-137 must still be taken seriously as a possible "dark horse."

Several specific caveats deserve mention. In the first place, because of its tendency to accumulate in muscle tissue, it will, to a much greater extent than Sr-90, be ingested via meat. Whether it is actually concentrated by animal metabolism (i.e., favored over potassium) is not yet established with certainty, though some degree of concentration may occur.

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*The fact that cesium is relatively unavailable via soil uptake, even from the start, is already taken into account in the empirical determination of A,B. The two-year cutoff for the cumulative term (B) is due to the rapidity of further decrease.

Again, in certain specialized communities the danger from Cs-137 may be significant. One of the objections raised to the AEC's project CHARIOT--a proposal to dig a harbor in Alaska using nuclear explosives--was based on such a situation. Apparently, Cs-137 deposited on reindeer moss (a lichen) is ingested by and accumulated in the bodies of caribou, thence passed on to Eskimos, who depend heavily on caribou meat and milk. Although the radiation level from testing was generally less in Alaska than in other states, the Cs-137 level in Eskimos' bodies was several hundred times higher in 1964 than the U.S. average.[150]

A final point of some importance is that the existence of a long-term Cs-137 hazard, even if it is only 5% of the magnitude of the Sr-90 hazard, tends to put an upper limit on what can be achieved by means of counter-measures directed specifically at the latter. For example, if people should cut down on consumption of grain products and increase consumption of meat, the risk from cesium ingestion would also increase in proportion.

I-131 is a short-lived isotope (8 days) which is, however, highly concentrated by human or animal thyroid glands, where it persists for considerable periods (~ 90 days) on the average.[151] Since I-131 provides a non-negligible portion (~ .8%) of the initial γ-radioactivity and 8% of initial β-activity of a typical fission-product mix (see Figure 1.1), it must be considered a serious hazard for several months. Almost the only means of entering the human diet within this short time is via milk,[152] water, or in fresh fruits or vegetables in season. Drying, freezing or canning would permit the contaminated food to be consumed later (provided Sr-90 was not also present in considerable quantities) with relative safety. Once in the body the radiation damage is largely concentrated in the thyroid gland. On the basis of experience on Rongelap Atoll in the Marshall Islands, where 82 people were accidentally exposed to fallout (averaging 175 R whole body dose) in 1954, the thyroid damage typically seems to take the form of benign nodules. In the first 10 years of medical examination three such cases appeared among girls who had probably received thyroid doses between 700 and 1,400 rads.[153] In the 11th year (1965) three additional cases were turned up in March and several more in September.[154] The nodules are apparently not malignant, but the appearance of pathological symptoms on such a scale gives rise to serious misgivings.*

The foregoing does not throw much light on the effects of radio-nuclide cycling elsewhere in the environment. One reason is that the human food chain has been artificially simplified. In the United States about a quarter** of the food for human consumption comes directly from cultivated plants, and well over 90% of the remainder is derived from domestic animals fed (66%) on cultivated plant sources and (33%) on natural pasture.[155] Almost the only foods arising from more complex chains are seafoods and fresh water fish.

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*Recent reports in the press (November 4, 1965) set the number of cases of thyroid abnormalities at 18, of which 8 are said to have been operated on and one to have been found to be cancerous.

**In terms of Calories.

Another reason is that internal hazards to humans (and large animals) are almost exclusively of the long-term variety, e.g. cancer, leukemia, life-shortening and genetic damage. Acute lethal internal doses are so unlikely that the possibility can be ignored in practice because of biological discrimination, the comparatively long time lag between contamination and consumption of food, the low rate of consumption in proportion to body weight, the possibility of monitoring radiation levels in food, and the fact that external doses or other effects would result in death long before internal levels could become critical.

It is important to note that in other segments of the ecosystem these ameliorating factors would not necessarily operate, at least to the same degree. Small animals and insects, for example, commonly consume several times their own body weight of food each day. The time lag between contamination, consumption and incorporation in tissue may be negligible. Thus isotopes such as I-131 which are chemically indistinguishable from their non radioactive counterparts are likely to be concentrated in animal tissue far beyond their proportional occurrence in the environment as a whole. It is not inconceivable that lethal (or sterilizing) internal doses could be accumulated in this way by some organisms faster than lethal external doses.

To date, radio-nuclide cycling in insect and animal food chains seems to have been studied hardly at all.* Yet such studies may be of considerable significance.

Since there are some two hundred radio-nuclides involved in the decay-chains of fission products--not to mention neutron-induced activity--some of which decay fairly slowly**(see Figure 1.1 and Table 1-1), the possibilities for

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*A few related studies exist:

(1) Genetic studies based on feeding the isotope P-32 to induce mutation (on the fruit fly *Drosophila melanogaster* and *Drosophila virilis*).[156]

(2) Studies of the distribution of P-32 in wax moth, meal worm, cockroach and firebrat.[157]

(3) Genetic studies using P-32 on the parasitic wasp *Habrobracon*. (It was found that 60% of the P-32 fed to females was incorporated into eggs, leading to some degree of infertility.) Studies have also been made of *Habrobracon* reared on host larvae injected with Ca-45 and Sr-89 isotopes. Both were incorporated in sperm but are not found in adult tissues.[158,159]

(4) Ecological studies of the consequences of waste disposal near Oak Ridge indicate that herbivorous insects accumulate Cs-137 (in muscular tissue, mainly) to the extent of the contamination in their food, but that Sr-90 is somewhat discriminated against. Ecological studies of the aquatic systems in the vicinity of AEC installations also have followed isotopes (mainly P-32) from algae into the fish and waterfowl food chains.[160,161]

(5) Ecological studies using P-32 as a tracer to untangle complex food chains.[162]

**In this context "slowly" would mean having a half-life comparable to or longer than the metabolic half-life of the isotope.

biological concentration in the food chain are very real. Moreover, since insects presumably have qualitative metabolic similarities, there is some probability that if an insect concentrates isotope "X," then its predator (or prey) may also concentrate it. Hence, for slowly decaying isotopes or rapid metabolic processes, the inherent likelihood of damage could conceivably increase with trophic level. That is to say, the higher the position in the food chain, the higher the probability of ingesting dangerous amounts of radioisotopes due to concentration by the previous steps in the chain. Admittedly most of the radio-nuclides decay very fast even compared to insect metabolic cycles, so that in many instances the effect of concentration is balanced or outweighed by the rapid decay. These cases are probably the least interesting, since the effect works in reverse: the prey gets larger internal doses than the predators. However, the significant point is that biological concentration is more likely to be important for insect predators with short life cycles and high metabolic rates than for larger animals such as birds or fish with longer life cycles and much slower feeding rates. Table 1-9 illustrates one case (P-32 in an aquatic food chain) where radioactive decay does at first balance, and finally outweigh, biological concentration.

At present there are few data applicable to this subject. Information on the cycling of radioisotopes among insect and invertebrate populations is probably potentially as important as information on their individual radiosensitivities to external γ or β radiation from the environmental point of view. Theoretical work done by Sparrow, _et al_., makes it possible to predict with reasonable success (e.g. within 25% or so) the radiosensitivities of different orders and species of plants and, possibly, of insects in the early stages of their life cycle. Much less experimental or theoretical work has been devoted to prediction of the movements of radioisotopes within complex animal food chains, although mention should be made of the work of Bowen and others on mineral metabolism in insects,[163] and, of course, Auerbach and his colleagues at Oak Ridge.[164]

Table 1-9

Cycling of Radio-phosphorus in Aquatic Food Chain (Columbia River, near Hanford)[165]

	Microcuries P-32 per gram of P-31
water	25
plankton	25
sessile algae	25
sponge	20
caddis worms	17
snails	8
fish	5
crayfish	2

P-32 half-life = 14 days
Materials were collected at different times, hence comparisons are of dubious value. See below:

	Time of peak radioactivity from one injection of P-32*	
water	0	hours
plankton	10	"
side-wall algae	5-10	days
animals feeding on side-wall algae	11-18	"
mud algae	15-25	"
sediment	still increasing after 50 days	

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*For water having low initial P-31 content, only 2-5% of P-32 remains after 30 days. For initial high P-31 concentration, 80-90% of P-32 remains (allowing for decay).

7. Sensitivities of Ecosystems

Radiation sensitivity of complete ecosystems is not a very well-defined notion. Studies of the effect of actual radioactive fallout on ecosystems as a whole--including both external and internal effects--have been mostly ex post facto, e.g. observations made after a nuclear test has taken place. The ambitious cooperative programs of the University of Washington (with regard to nuclear testing in the Pacific) and New Mexico Highlands University and Brigham Young University (in conjunction with the testing in Nevada) are of this type. Similarly the ORNL and Hanford programs are carried out in conjunction with disposal of radioactive wastes. Such studies are well-suited for investigating food chains and cycling of radio-nuclides, but inherently inappropriate for obtaining quantitative data on ecosystem response to radiation. The AEC did an extensive ecological study in anticipation of a PLOWSHARE project to use nuclear explosives to dig a harbor in Alaska; although the project (CHARIOT) has been shelved.[166]

Major programs suited for determining ecosystem sensitivity and response to γ-radiation from external sources (usually Co-60) are carried on at Brookhaven and Emory University, Georgia, though small-scale studies exist elsewhere. The Oak Ridge program seeks to obtain similar data for fast-neutron irradiation. Such information as is now available is not suitable for compact tabular presentation, but reference was made to specific data elsewhere in this chapter.

Table 1-10

Studies of Irradiated Ecosystems

	(References)
Dry lake bed in Tennessee	89,98,160,167
Nevada test site (desert community)	168,169
Abandoned cornfield in Georgia	170
Granite outcrop in Georgia	171
Oak-pine forest in Georgia	172
Oak-pine forest in Long Island	173,174,175
Abandoned potato field ("old field") in Long Island	175
Coral atolls in Marshall Islands	176,177
Mixed forest in Tennessee	178

Rongelap atoll in the Marshall Islands has received the greatest amount of fallout (as a result of an unexpected wind shift at the time of the 15-MT test detonation BRAVO at Bikini, 121 miles to the west, on March 1, 1954)--and the most concentrated attention since that time. The most heavily irradiated islet (Gegen) received an estimated dose of 3,000 R.[179]

In the whole area the flora consisted of 43 species, all specialized to tolerate conditions of high salt concentration, heat and low humidity. Of these, only 20-odd grew on the islets where fallout was heaviest; by 1956, 16 species were visibly affected. Two very abundant and well-adapted species showed no abnormalities, while at the other extreme three species were severely damaged. One plant species was completely killed on Gegen. By 1956, insect populations were essentially normal, although some evidence of genetic damage--including mutants--was noted in the area. The 182 humans in the area received average doses of 175 roentgens and some had serious β-burns (especially on bare feet), but none died. There is recent evidence suggesting thyroid damage, due to ingestion of I-131, may have been fairly widespread, as discussed earlier. All inhabitants are now back, after having been temporarily evacuated for treatment and observation. The only significant difference between life today and in 1954 is that inhabitants still do not eat cocoanut crabs, formerly a dietary staple, because of the continuing Sr-90 hazard.

Bikini and Eniwetok, where 100 MT's of test explosions actually took place as recently as 1958, were revisited by a scientific expedition from the University of Washington in 1964. According to reports in the press, apart from the actual craters, which are still visible, vegetation seems to have returned to normal. The rat population is also back at normal levels and no visible abnormalities were found, although some genetic damage cannot be ruled out. One of the few notable differences is that clams, formerly abundant, are no longer found in the surrounding waters. This is attributed not to radiation, however, but to the fact that much of the underlying coral was powdered by the blasts and that clams cannot live in silty water.

The following table summarizes the sensitivities of several important communities or biomes, as currently known or estimated.

Table 1-11

Radiosensitivities of Communities

		LD_{50-30} (R)	D_E(crit)* (KT/mi^2)
Vertebrates	Mammals	300-800	--
	Birds	~1000	--
Insects (8 species, sterilization dose)		1000-6000	--
Conifers (5 species)		750-1000	~.06
Wheat, corn, oats, rye, barley		3000	~.18
Sorghum		~5500	~.33
Deciduous trees (5 species)		~6000-7000	~.45
Potatoes		~9000	~.55
Soybeans		~10,000	~.60

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*Based on accumulated 30-day dose from uniformly distributed fission products, and assuming LD_{90}'s are about 25% higher than LD_{50}.

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CHAPTER II

PRIMARY THERMAL EFFECTS

1. Introduction

Blast and radiation effects of nuclear weapons dominated public interest for some years. It is only more recently that the thermal effects of nuclear weapons have received the same degree of attention. Interest in this aspect of nuclear weapons was heightened by the Soviet testing in 1961 of a very large yield nuclear (60+ megatons) weapon. Since dangerous thermal effects can extend to much greater distances than either blast or initial (nuclear) radiation, weapons of large yield raise the possibility of high-altitude bursts intended to maximize fire effects. Such detonations would leave no significant blast damage and would present no early fallout hazard. It is worth remembering that the enemy has a choice of optimizing fallout or thermal effects, but not both at the same time. Fallout is maximized by surface bursts. However, in this case fewer potential ignition points are exposed to direct thermal radiation since part of the radiation energy is absorbed in the ground and the debris in the fireball itself and the area of shadows cast by irregularities of terrain, etc., would be greater. Many types of attack are possible and detailed studies would require a "gaming" approach making alternative assumptions as to the choice of targets for attack, the types and number of weapons, the choice of air or surface bursts, etc. In almost any attack, it is probable that some detonations would occur over forest areas simply as a result of aiming errors, missile malfunction and the proximity of forest lands to primary targets. And the question is whether the enemy would make wildland areas a primary target subsystem or whether damage to these areas would be incidental to attack on military targets and urban areas. It is probably reasonable to assume, for most scenarios, that an enemy would allocate the majority of his weapons to targets such as strategic weapon sites or cities. However, a possibility worth considering is that an enemy might choose a "sophisticated" strategy, e.g. demonstrating resolve without killing people; alternatively, in some future situation cities and populations might be effectively protected by active and passive defense, leaving the "B-country" as the most lucrative available target (although this would suggest a less than optimal, that is, unbalanced, defense).

2. Ignition

As a rule of thumb, materials which can be easily ignited by a single match can also be ignited by the thermal pulse of a (megaton) nuclear detonation. If the fuel would char or shrivel rather than burn, as in the case of green vegetation, then a nuclear explosion would probably cause the same result.[1]

Kindling fuels have been graded into three categories according to their degree of inflammability. The most inflammable group, typified by newspaper, includes such natural fuels as dried deciduous leaves, fine grasses, duff and rotted wood (punk). The second group encompasses such items as small twigs, birchbark, Kraft corrugated paperboard, and light fabrics. The third and least inflammable type includes heavier twigs, thicker bark, wood chips, pine cones, drapery-weight fabrics and miscellaneous fuels of equivalent thickness. Typical ignition exposure levels as a function of (low) airburst weapons yield are given in Table 2-1.[2]

Table 2-1

Approximate Ignition Thresholds for Several Common Kindling Fuels (Low Airbursts)

	Ignition Thresholds (cal/cm^2)		
Kindling Fuels	1 MT	10 MT	100 MT
Punk and dry, thin deciduous leaves	6	8	~30
Newsprint, dark picture area, crumpled	7	11	25
Kraft corrugated paper carton (18 oz/yd^2)	25	38	~50
Heavy dark cotton drapes (9 oz/yd^2)	~18	~34	~50
White typing paper	30	50	~80

As weapon yield increases, for explosions at altitudes designed to optimize blast damage (the area inside a 15-psi contour), the ignition thresholds are increased slightly as Figure 2.1 shows. The ignition values in the table are also increased by a factor F which depends on humidity, e.g.,

$$F = 1 + 0.005\ H$$

where H is the relative humidity in per cent. (At 50% humidity, F = 1.25; at 100% humidity, F = 1.50.)

The area over which ignitions would occur depends on the altitude and yield of the burst and is a function of prevailing atmospheric and fuel conditions. The transmissivity of the atmosphere over long ranges is still poorly known, and therefore a major source of uncertainty. Up to the limit of visibility, which is roughly as far as experimental test data were taken at the Nevada Test Site and elsewhere, the uncertainties may be 25%-50%, while at greater ranges, where data are lacking, the uncertainties are much greater, especially for low airbursts. The curves shown in Figure 2.1 are based on extrapolations preferred by the Project Harbor panel of experts.[3] Figures 2.2 and 2.3 come from Martin and Holton.[4]

Table 2-2 summarizes the ignition hazards as far as present knowledge will permit. Since the degree of cloudiness is important, it is interesting to note that the average U.S. city with population over 100,000 has only 125 "clear" days a year (only 10% have as many as 200) while on 130 days there is heavy cloud or fog, and on 110 days it rains. The map (Figure 2.4) shows the geographical distribution of cloudy areas.[5] Agricultural areas are, on the average, less cloudy than the urbanized northeast and upper midwest (Great Lakes) region where many of our cities are located. However, "average" conditions are almost meaningless because of wide seasonal fluctuations as will be discussed later. The area of probable ignition can be crudely estimated in another way on the following basis: we assume the

FIGURE 2.1

THERMAL FLUX FOR AIRBURSTS DESIGNED TO OPTIMIZE BLAST DAMAGE AS A FUNCTION OF RANGE

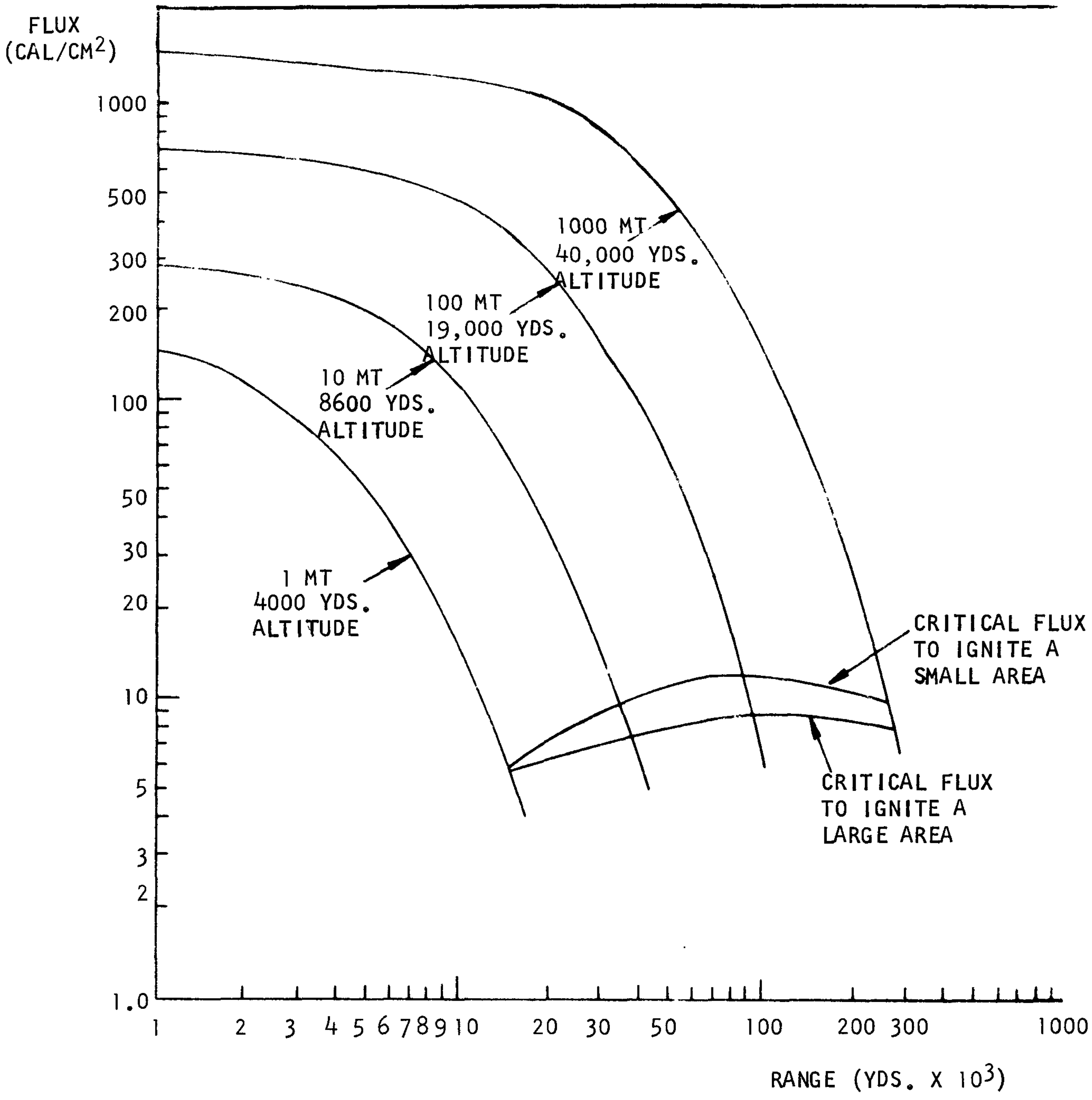


FIGURE 2.2

EXPOSURE RANGES FOR 10 MT WEAPONS

NO CLOUDS
SURFACE AT SEA LEVEL

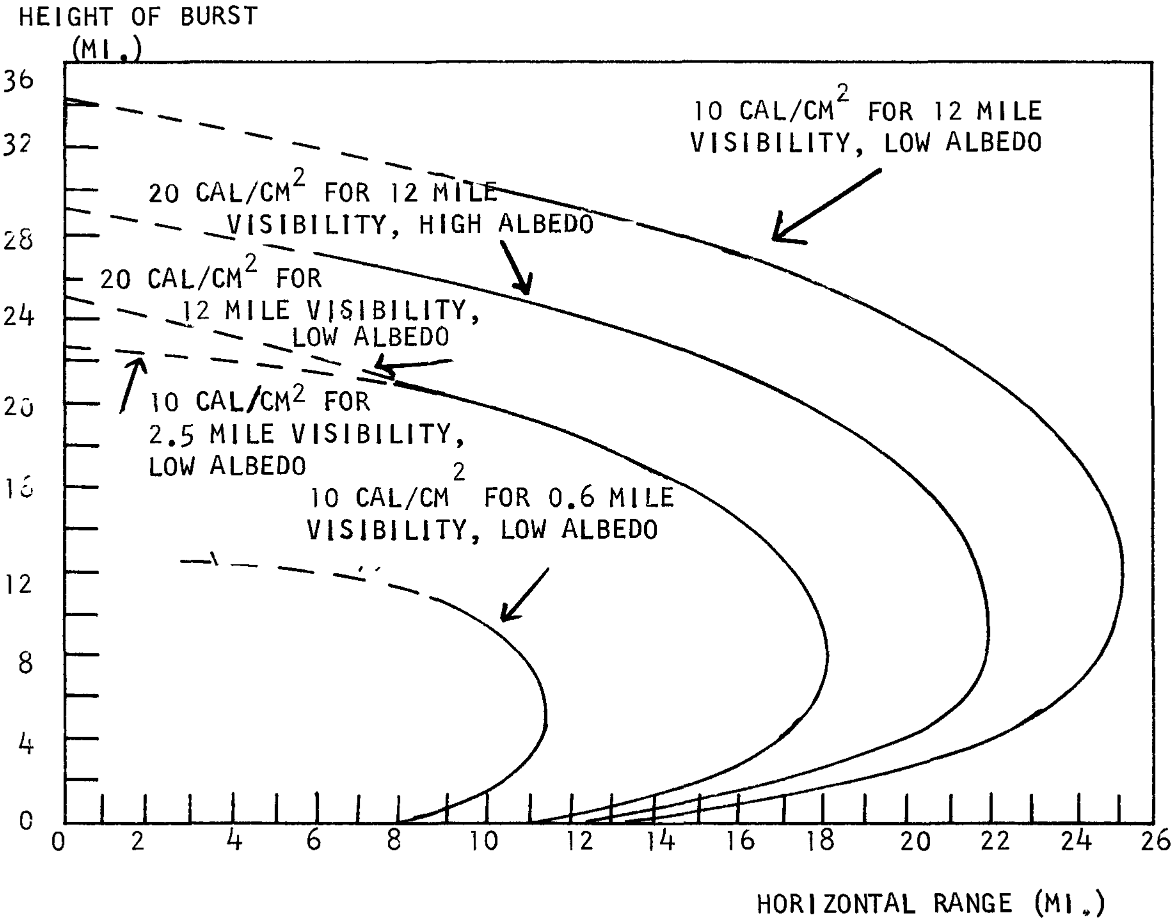


FIGURE 2.3

IGNITION RANGES FOR 10 MT WEAPONS

NO CLOUDS
SURFACE AT SEA LEVEL
12 MILE VISIBILITY
50% HUMIDITY

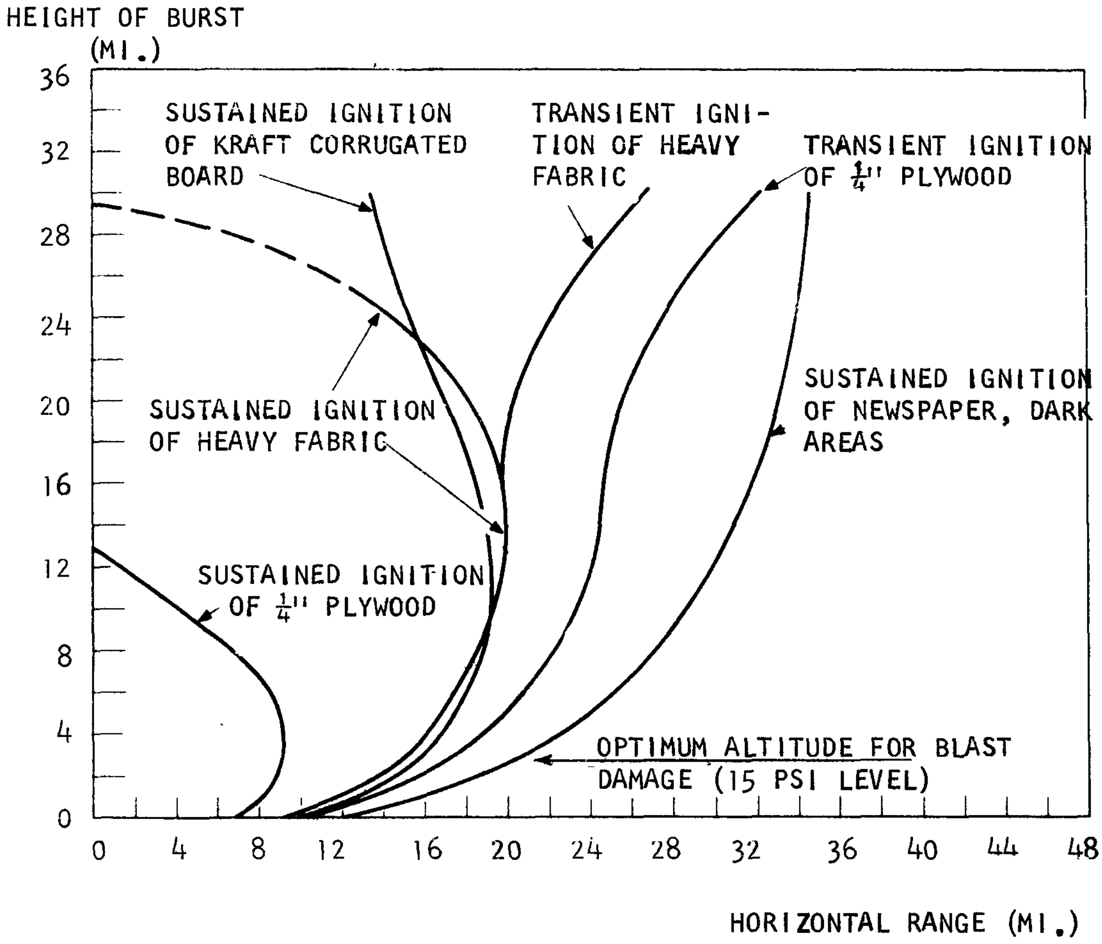


FIGURE 2.4

AVERAGE ANNUAL PER CENT OF OPAQUE CLOUDINESS (ATTENUATION FACTOR ≲0.1)

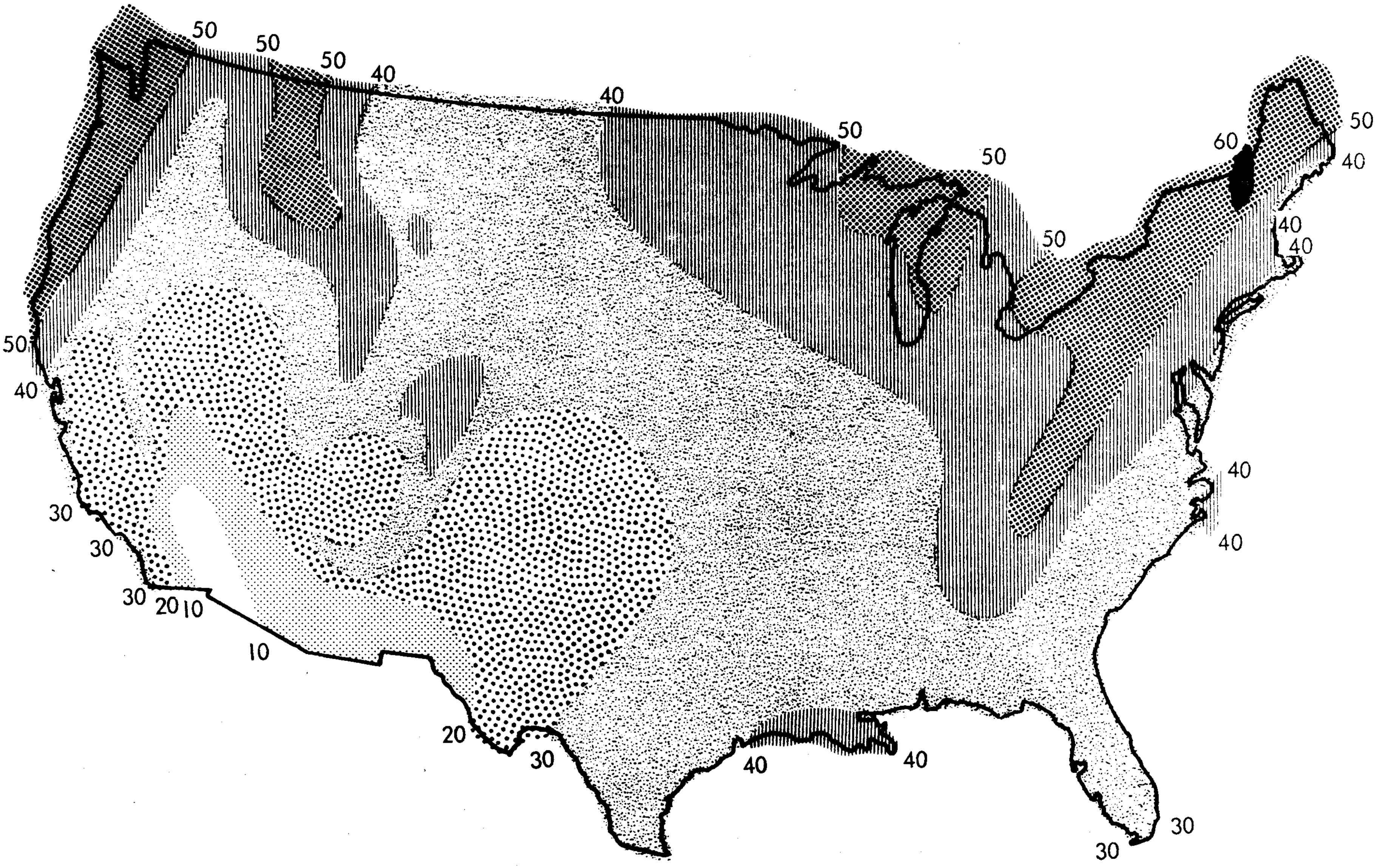


Table 2-2

Limits of Thermal Ignition (Optimized Airbursts)

Cloud Cover	Attenuation Factor	1 MT Range of fine fuel ignition (6 Cal/cm^2) (mi.)	Area (mi^2)	10 MT Range (10 Cal/cm^2) (mi.)	Area (mi^2)	100 MT Range* (10 Cal/cm^2) (mi.)	Area (mi^2)
Average clear	1.0	9	255	21	1400	55	10,000
Light haze	0.7	7.8	190	18	1000	50	7,900
Medium haze	0.5	6.7	140	15	700	46	6,600
Heavy cloud	0.1	2.7	23	6	110	24	1,800
Dense cloud	0.03	neg.	neg.	neg.	neg.	11	380

threshold for ignition (from megaton-class weapons) is 10 cal/cm^2. Approximately one-third of the energy of a thermonuclear explosion in the lower atmosphere takes the form of thermal radiation. In the case of very large, very high-altitude detonations, the fraction will be higher. Assuming isotropic emission, roughly one-third of this--allowing for geometry and atmospheric attenuation--will intercept the surface of the earth within a radius of 20 miles or so on a clear day. (The radiant energy intercepting the earth at 20 miles slant-range from a 10-MT detonation at optimum altitude will be just about 10 cal/cm^2.) Thus, roughly 10^{15} cal (out of 10^{16} total)* are distributed within this area of about 1260 mi^2 or 3×10^{13} cm^2.

Assuming the radiant energy which actually intercepts the earth were distributed evenly, rather than according to the more nearly correct inverse square law, the 10 cal/cm^2 critical ignition level implies a distribution of thermal energy on the ground equivalent to about $\sim .25$ KT/mi^2. To express this in terms of KT/mi^2 gross yield, a quantity used often in damage-assessment calculations, we divide by the efficiency with which a megaton weapon deposits thermal energy on the ground on a clear day (a factor estimated above to be $\sim .1$). Thus we have the rough equivalence:

$$10 \text{ cal/cm}^2 <=> 2.5 \text{ KT/mi}^2$$

To convert energy deposition figures, given for convenience in terms of KT/mi^2 gross yield, where the weapons are exploded in some complex pattern and, of course, the weapons effects are not optimally (i.e., uniformly) distributed over the landscape, a further inefficiency must be allowed for. Thus, to obtain the actual number of weapons required to achieve the same effect as we have initially calculated on the uniform basis means dividing by another small number which is a function of weapon size and distribution. For the particular case of the single 10-MT weapon exploded at optimum altitude, we noted that an area of 1260 mi^2 was subjected to a flux greater

---

*1 MT = 10^{15} calories.

than or equal to the critical value of 10 cal/cm^2. Optimum deposition of this energy would have required just 3×10^{14} cal., whereas actually 1.0×10^{15} cal. is deposited inside the perimeter in addition to a small amount outside. Thus, more than 70% of the thermal energy is "wasted." An efficiency of deposition of ~.1 or 10%, multiplied by an efficiency of utilization of about 0.3 corresponds to an over-all ignition efficiency of ~.03 or an <u>inefficiency</u>

$$Q_T \cong 33$$

The distance from ground zero at which a given quantity of radiant flux is received (per unit area) varies at a rate between the cube root and the square root of the yield, whence the area affected varies as a fractional power (< 1) of yield. Consequently, smaller weapons are somewhat more efficient at starting fires than large ones (in terms of area ignited per MT), at least in the case of optimized burst altitudes. For example, a 1-MT bomb exploded on a clear day has only 10% of the yield, but might ignite fires over an area of about 18% of the area covered by a 10-MT bomb. However, in some circumstances, as will be explained later in Chapter IV, section 6, the scaling law for recovery works the other way, i.e., a larger weapon is more efficient in terms of ultimate disutility to the target area.

For the sake of symmetry we could also introduce a "shielding" inefficiency S_T. Thus, in the case of a 10-MT weapon burst at optimum altitude in medium cloud, the ignition range (10 cal/cm^2) may be reduced from 21 to 9 mi.--which happens to be the range at which a 1-MT weapon would cause ignition (6 cal/cm^2) on an average clear day. Thus, in this case, one might define the shielding inefficiency as

$$S_T \cong 10$$

since the shielding of the cloud, as compared to a clear day, reduced the effectiveness of the 10-MT weapon to that of an "equivalent" 1-MT weapon. This method of comparison is somewhat artificial, however, since one must choose burst and ignition criteria differently. Also, in general, one would have to perform scaling calculations which involve more than simply reading from Figure 2.1 or Table 2-2. Hence we shall not in practice depend heavily on the concept of a thermal shielding multiplier, except to note that such a number can be defined, once the "equivalence" rules are specified, and that in many instances the multiplier would be rather large.

3. Fire Spread

The problem of estimating fire spread criteria can be understood somewhat better--if not fully illumined--by focusing on the known conditions for "no spread."* These have been summarized by Chandler, Storey and Tangren[6] as follows:

All Fuels:	over 1 inch of snow on the ground at the nearest weather reporting stations.
Grass:	relative humidity above 80 per cent.

---

*i.e., rate of spread less than .005 mph.

Brush or Hardwoods: 0.1 inch of precipitation or more within the past 7 days and--

Wind 0-3 mph; relative humidity 60 percent or higher, or
Wind 4-10 mph; relative humidity 75 percent or higher, or
Wind 11-25 mph; relative humidity 85 percent or higher.

Conifer Timber: (a) 1 day or less since at least 0.25 inch of precipitation and--

Wind 0-3 mph; relative humidity 50 percent or higher, or
Wind 4-10 mph; relative humidity 75 percent or higher, or
Wind 11-25 mph; relative humidity 85 percent or higher.

(b) Or, 2-3 days since at least 0.25 inch of precipitation and--

Wind 0-3 mph; relative humidity 60 percent or higher, or
Wind 4-10 mph; relative humidity 80 percent or higher, or
Wind 11-25 mph; relative humidity 90 percent or higher.

(c) Or, 4-5 days since at least 0.25 inch of precipitation and--

Wind 0-3 mph; relative humidity 80 percent or higher.

(d) Or, 6-7 days since at least 0.25 inch of precipitation and--

Wind 0-3 mph; relative humidity 90 percent or higher.

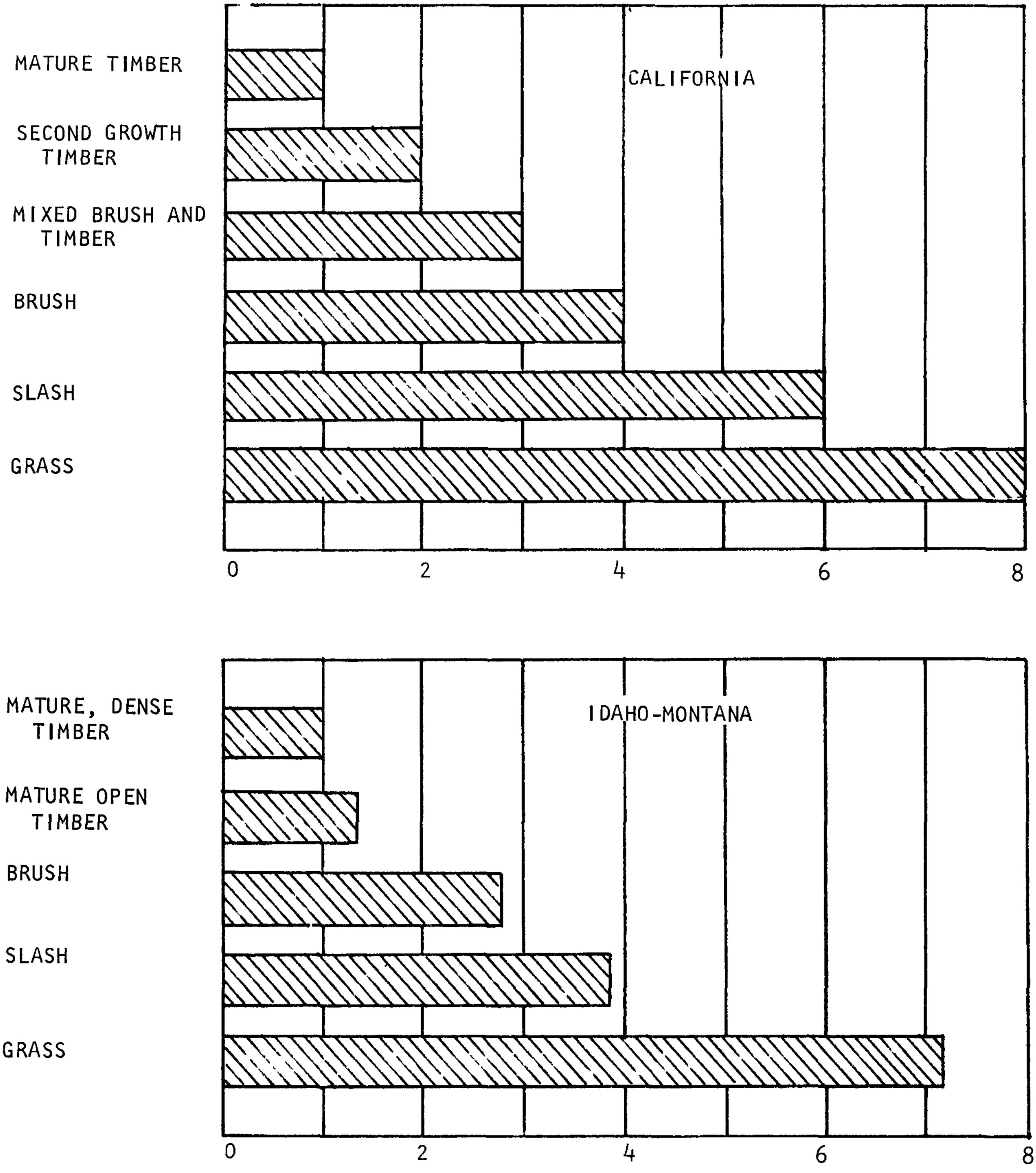
By testing against over 4,000 actual fires, where detailed weather conditions were known, it was determined that the criteria were quite accurate in the sense that in virtually 100% of the cases where "no spread" would have been predicted, there was in fact no spread. On the other hand, about 60% of the fires, where the "no spread" criteria were not fully met, also did not spread. This suggests that "will spread" criteria are not simply complementary to "no spread" criteria. Other conditions besides, are required to ensure that a fire will burn.

Apart from humidity and recent rain, it is clear that some fuels are much more easily ignitable than others. Highly combustible fuels such as grass will dry out quickly and may be easily kindled by burning embers. Conversely, heavy, damp logs must be heated for quite a long time before they will dry out sufficiently to burn. These differences affect rates of fire spread, as shown by the following graphs (see Figure 2.5) taken from Chandler, Storey and Tangren.[7] Taking mature timber and grass as extremes, it will be noted that there is a difference of 7-8:1 in intrinsic rates of spread, other things being equal.

One factor (among several) worth mentioning is topography: it is an empirical fact that forest fires spread more rapidly uphill than downhill, by a factor of about two for each 15 degrees of slope. This would be extremely

FIGURE 2.5

RELATIVE RATE OF FIRE SPREAD, BY FUEL TYPES



significant in areas of steep slopes. Spread uphill would generally be extremely rapid, but a steep downward slope is very close to being a firebreak unless burning material is dislodged and rolls downward, spreading the flame front discontinuously. Whether this would happen depends on the roughness of the ground and the nature of the undergrowth. It is apparently a not infrequent mode of fire progression in certain western forests. However, it appears that the net effects of upslopes and downslopes tend to cancel over large areas and cannot be detected in the best available data.[8]

A reasonable degree of density and contiguity of fuels* is evidently a prerequisite for any mass fire. The presence or absence of effective firebreaks is especially critical. The width of firebreak necessary to stop a fire depends on the size of the burning area (up to fires a mile or so in diameter--discussed later) and on the wind velocity at the fire front. A gap of a few inches or even less is likely to stop the spread of fire from a primary ignition, e.g. a single match or burning ember. A good-sized bonfire is capable of jumping a gap of several yards, and so on. Fire spread depends--other things being equal--on the pattern of disposition of combustible and incombustible areas, i.e. fuel and firebreaks. Averaging over all these factors, one typically gets a curve something like Figure 2.6 (although the ones shown refer to urban fires).[9]

The various considerations outlined above must all be involved in any satisfactory theoretical model for predicting rates and extents of fire spread following a given set of initial conditions. Some efforts are under way to develop and improve such models, but sophistication and accuracy of predictability are currently rather low.

One model for large-scale computer calculations (called FLAME I) has been developed under contract to the National Resources Evaluation Center of the Office of Emergency Planning. A detailed description of the assumptions and approximations used in it would be out of place. The designers themselves point out that it is severely limited by the constraints imposed by the allowable running time on the computer. Moreover, they remark,

> "...it is not possible to get good information on fire behavior and the factors affecting fire spread, hence any model which is too sophisticated and attempts to take too much into consideration would only fool the user into a false sense of security with respect to the accuracy and meaning of his results."[10]

The basic scheme of the model is an assignment of burning probabilities to discrete areas, each one assumed to be homogeneous in terms of fuel density, moisture, etc. Fire spread is allowed to occur in discrete "quantum jumps" until the cumulative probabilities of burning the next region fall below a preassigned number, e.g., .5. External weather conditions are assumed to influence the probabilities, but non-linear effects--

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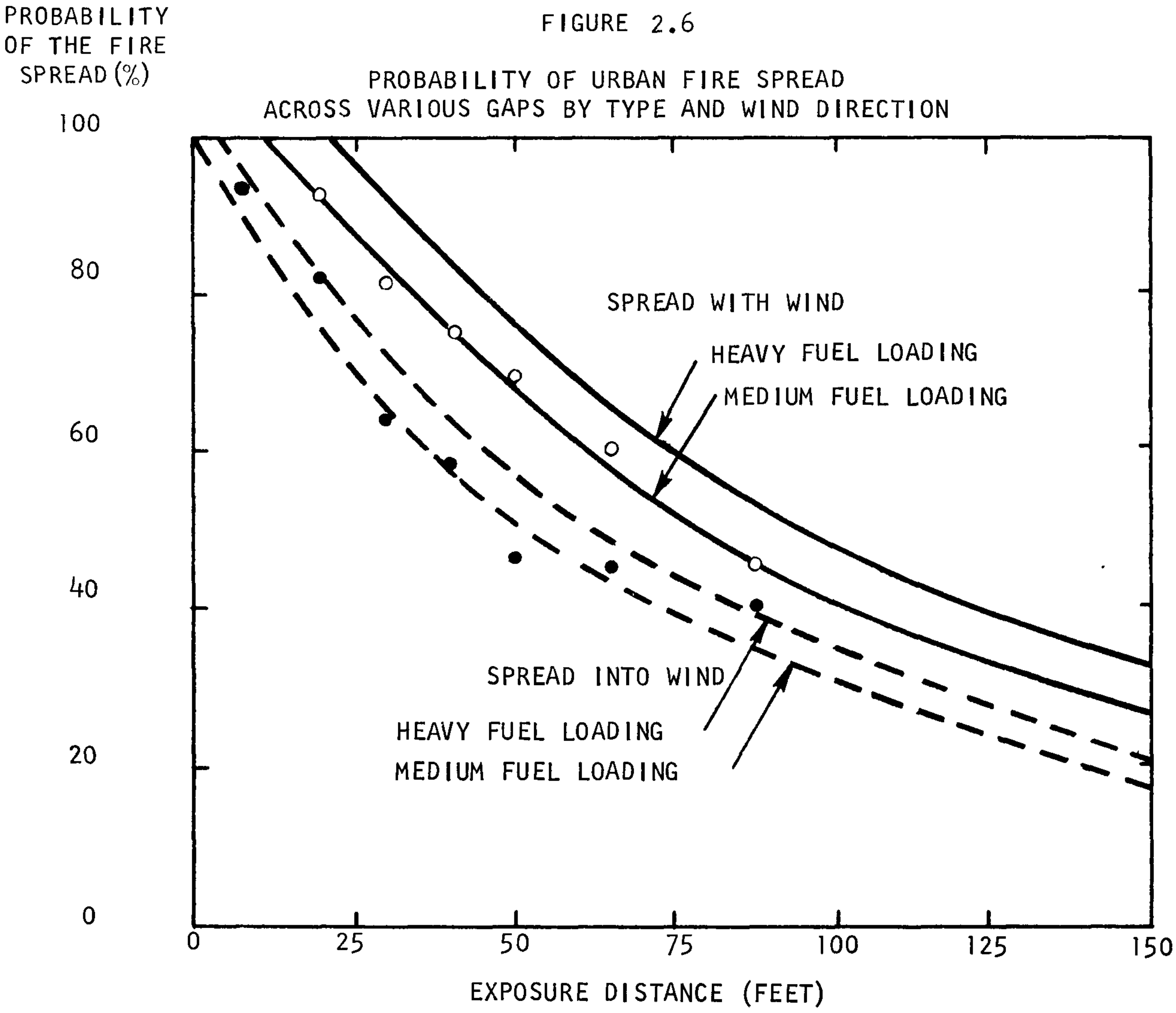
*In studies of city fires this notion is expressed as degree of "built-upness."

FIGURE 2.6

PROBABILITY OF URBAN FIRE SPREAD ACROSS VARIOUS GAPS BY TYPE AND WIND DIRECTION



as where the fire creates its own weather--do not occur in the model. Since this is the fundamental distinction between firestorms and conflagrations, as we shall presently point out, the model essentially applies only to the latter.

Other research on postattack firespread models pertinent to the rural/wildland case has been done, notably by Phung and Willoughby (URS).[11] The URS work examines the basic prerequisites for several "levels" of models, e.g., purely empirical, semi-empirical, purely theoretical (i.e., analytical) and concludes that neither the first nor the third is currently feasible. Several semi-empirical models are derived, of various degrees of sophistication and utilizing both deterministic and stochastic approaches. In most cases the data needed to fix the parameters of the models is found to be inadequate or nonexistent. The two needed parameters--which would be combined with other available data--are

a. the mean lifetime of a fire (as a function of fuel density, type, weather conditions, etc.)

Table 2-3

Violent and Residual Burning Times, by Fuel Type

Fuel Type	Violent Burning		Residual Burning	
	Time	Total Energy Release	Time	Total Energy Release
	min.	%	min.	%
Grass	1½	>90	½	<10
Light brush (12 tons/acre)	2	60	6	40
Medium brush (25 tons/acre)	6	50	24	50
Heavy brush (40 tons/acre)	10	40	70	60
Timber	24	17	157	83

FIGURE 2.7

TYPICAL DISTRIBUTION OF TEMPERATURE IN RELATION TO BURNING TIME

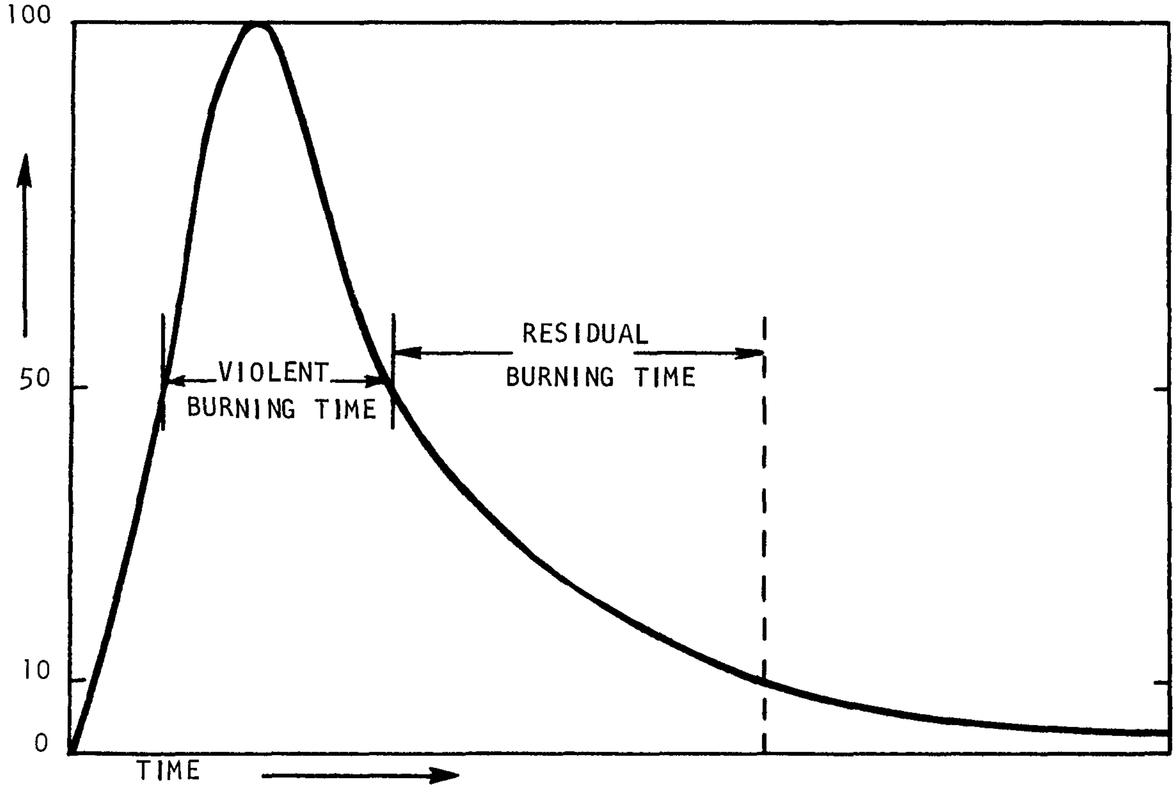


Table 2-4

Probability of Critical Conditions: Fire Would Spread Uncontrollably

Regions	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Northeast Region (NE)	.00	.00	.00	.00	.01	.00	.01	.00	.00	.00	.00	.00
Southeast Region (SE)	.00	.00	.00	.01	.01	.01	.00	.00	.00	.00	.00	.00
Lakes States Region (LS)	.00	.00	.00	.01	.02	.01	.00	.01	.01	.01	.00	.00
Ohio & Middle Mississippi Valley Region (OMMV)	.00	.00	.00	.01	.01	.01	.01	.01	.01	.02	.01	.00
West Gulf States Region (WG)	.00	.01	.00	.01	.00	.00	.00	.01	.02	.01	.00	.00
Southern Plains Region (SP)	.06	.09	.16	.15	.11	.17	.16	.18	.18	.14	.10	.08
Northeastern Plains Region (NEP)	.00	.00	.00	.03	.05	.02	.02	.02	.05	.04	.00	.00
Northwestern Plains Region (NWP)	.00	.00	.01	.06	.08	.12	.18	.23	.22	.14	.04	.00
Northern Rockies & North Intermountain Region (NRNI)	.00	.00	.00	.01	.02	.06	.18	.18	.10	.04	.01	.00
Central Intermountain Region (CI)	.00	.01	.04	.14	.22	.42	.51	.46	.40	.15	.03	.01
Southwest Region (SW)	.13	.22	.45	.58	.72	.79	.48	.31	.51	.33	.20	.11
Pacific Northwest Region (PNW)	.00	.00	.00	.00	.00	.01	.03	.02	.01	.01	.00	.00
Northern & Central California Region (NCC)	.00	.00	.01	.01	.03	.09	.12	.15	.11	.06	.01	.00
Southern California Region (SC)	.03	.04	.07	.04	.15	.24	.35	.38	.34	.26	.24	.14

Table 2-5

Probability of "Actionable" Conditions: Fire Would Spread Unless Control Measures Were Taken

Regions	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Northeast Region (NE)	.01	.03	.09	.29	.38	.35	.36	.30	.24	.21	.08	.01
Southeast Region (SE)	.14	.22	.33	.45	.44	.40	.36	.33	.33	.34	.26	.13
Lake States Region (LS)	.00	.00	.04	.29	.40	.36	.37	.31	.32	.26	.07	.00
Ohio & Middle Mississippi Valley Region (OMMV)	.07	.14	.24	.39	.40	.41	.40	.45	.54	.40	.25	.10
West Gulf States Region (WG)	.21	.22	.33	.37	.37	.48	.45	.52	.48	.46	.33	.19
Southern Plains Region (SP)	.35	.37	.43	.45	.45	.56	.61	.62	.57	.49	.48	.39
Northeastern Plains Region (NEP)	.01	.02	.10	.40	.49	.47	.43	.38	.47	.42	.24	.02
Northwestern Plains Region (NWP)	.12	.15	.20	.41	.48	.46	.57	.54	.53	.50	.28	.14
Northern Rockies & North Intermountain Range (NRNI)	.04	.06	.16	.45	.53	.59	.72	.72	.70	.46	.16	.04
Central Intermountain Region (CI)	.11	.18	.42	.55	.56	.50	.43	.45	.52	.64	.41	.16
Southwest Region (SW)	.52	.56	.42	.35	.23	.18	.40	.54	.43	.53	.59	.55
Pacific Northwest Region (PNW)	.01	.02	.03	.18	.23	.26	.45	.45	.38	.13	.04	.00
Northern & Central California Region (NCC)	.06	.13	.31	.45	.56	.65	.70	.68	.70	.62	.40	.18
Southern California Region (SC)	.28	.34	.30	.34	.28	.26	.21	.19	.25	.27	.30	.34

b. the mean burning time of various types of fuels under known conditions. The numbers shown in Table 2-3 and Figure 2.7 are considered by the authors insufficiently accurate for predictive purposes, although the data could probably be upgraded fairly readily.

Phung and Willoughby conclude that the best model available at present is one (which they describe) based on the assumption that fires (once ignited) either go out immediately or spread indefinitely until fuel or weather conditions change. Such a model would be based on the "no spread" conditions summarized previously, together with rates-of-spread data such as given by Figure 2.5. An earlier version of the URS work (known as the "Broadview Model")[12] was the basis of an attempt by the Forest Service to estimate <u>maximum</u> fire spread in each of 421 acres of the U.S. as a function of weapon size and month of the year.[13] The calculations cannot be evaluated adequately without a detailed critique of the assumptions used. However, we should point out that the USFS calculated fire spreads were considerably greater than those suggested in Table 2-6.

A model which is somewhat akin to the one described above will be used hereafter. It is difficult to estimate probable firespread, even crudely, because one cannot justifiably make the calculation on the basic initial assumption of "average" conditions. In the first place, the seasonal variation is such that actual conditions at a given time are likely to differ appreciably from the average. Data for various regions is shown in Tables 2-4 and 2-5 and on the map, Figure 2.9.[14] The probabilities exhibited in the two tables are for two mutually exclusive situations. We have not shown the corresponding data for the other two distinguishable cases, i.e., such that fires will not ignite, and such that fires will ignite but will go out without any action by firefighters.[15] Moreover, the "average" fire does not occur under "average" conditions: in fact, 75-90% of total fire damage is caused by 3-7% of the fires, which take place on 2-5% of the days of the year.*[16]

It is well known that the most destructive fires--corresponding to large values of i (see Appendix F)--are closely correlated with the occurrence of "fire weather" (low humidity, high wind, extended drought). Fires ignited under such conditions are nearly impossible to control, but continue to spread until the weather changes or the fuel is used up. Average fire spread under such conditions may be estimated crudely by (1) assuming a constant ignition probability throughout the part of the year during which ignition is physically possible, to account for the total number of catalogued fires, and (2) assuming the number of fires ignited during extreme burning conditions is proportional to the ratio of "critical" days to "possible ignition" days in the forested areas. To simplify matters further, we assume

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*Such skew distributions are actually fairly commonplace and occur in a wide variety of contexts. Simon has demonstrated rather convincingly that the similarity among diverse classes of such distributions arises because of common underlying probability mechanisms, which can be described by a stochastic model.[17] The basic assumptions can be stated in terms which make it plausible that the fire-damage distribution should be of the same general form. A sketchy outline of the argument is given in Appendix F.

that there are no significant forests in the Southern California (SC), Southwest (SW), Central Intermountain (CI), * Southern Plains (SP), Northeastern Plains (NEP), and Northwestern Plains (NWP) areas, and that the other areas contribute equally in terms of some appropriate measure of value at risk. See Table 2-4.

Covering the regions specifically not omitted, we find an annual average probability of 1.7% for critical fine weather conditions and 55.7% for possible ignition conditions;[18] which implies that roughly 3% of all ignitions in forests occur during critical conditions.** As pointed out earlier, these fires probably account for 3/4 or 4/5 of all acreage burned. Thus, the "average" fire <u>ignited during critical fire weather</u> burned approximately 1,000 acres or 1.5 square miles. Of the remaining fires roughly half would have occurred in "actionable but controllable" weather conditions and half under conditions requiring no action of any kind. On the basis of the assumed damage distribution function it is clear that most of the remaining damage was done by "actionable" fires. On this basis, the average fire in the "actionable" class would have burned perhaps 12 or 13 acres, while the remainder--half the total--accounted for a negligible proportion of the damage.

From the point of view of assessing probable fire damage from nuclear attack, it is clear that there are three roughly distinguishable cases:

a. no spread: about 50% of the ignitions;
b. actionable--moderate spread: about 50% of the ignitions;
c. critical--wide spread: about 3% of the ignitions in forested areas.

One can make a somewhat finer distinction with regard to seasonal variation. The probability of critical and actionable conditions is extremely low during the winter months (November-March) and highest in the summer (June-September). On the other hand, "no spread" conditions are most likely at times when critical fire weather is least likely.

Similarly, ignition radii will vary roughly in accordance with the same rule: critical firespread conditions will correspond roughly to maximum visibility;*** actionable conditions are more likely to correspond to intermediate visibility and "no spread" conditions to low visibility.

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*The weather conditions for the forested mountain areas of Colorado are probably not very typical of the area as a whole; hence it seems better to exclude this region.

**The omitted regions have some forests, and a generally higher probability of critical conditions, as Table 2-4 shows. However, the included regions are not uniformly forested, nor homogeneous as regards weather, and the resulting tendency is probably to overestimate the probability of critical conditions in the forested sections of these regions, which are typically in the hillier areas where rainfall is greater than the regional average.

***Maximum visibility will occur far more often, however.

Total area of spread can be estimated crudely by assuming everything within the "standard" ignition range (10 cal/cm^2) burns, contributing πR^2, and assuming a downwind spread in a fan-shaped pattern adding a term proportional to the ignition perimeter, i.e., $\sim \pi R$. The proportionality factor α, which we denote the "coefficient of spread," depends on the prevailing weather conditions. It can be estimated by means of the following device: assume a point ignition and a "distance of spread" α in the downwind direction. From the argument presented previously, we can equate the area of the fan-shaped region $1/4\ \pi R^2$ with the average areas burned in the three cases:

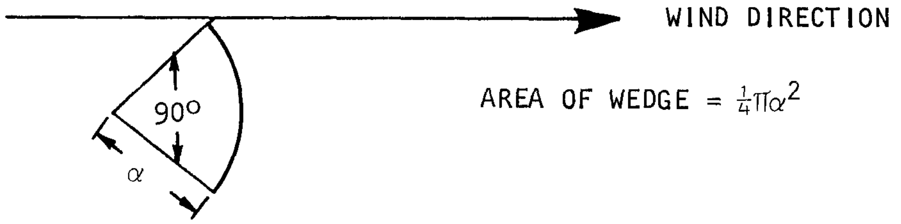
a. no spread: $\alpha \cong 0$
b. "actionable": $1/4\ \pi R^2 \approx 12$ acres or .019 mi^2
whence $\alpha \cong 0.15$ mi.
c. "critical": $1/4\ \pi\alpha^2 = 1{,}000$ acres or 1.5 mi^2
whence $\alpha \cong 1.4$ mi.

The area of spread downwind from a circular fire front (with radius R) can be approximated by the area of an annulus extending halfway around the circle (see Figure 2.8), viz., $\alpha[2 + (\pi/2)]R$. Evidently the total area burned would be

$$A = \pi R^2 + \alpha[2 + (\pi/2)]R.$$

FIGURE 2.8

FIRESPREAD FROM POINT SOURCE



FIRESPREAD FROM CIRCULAR LINE SOURCE

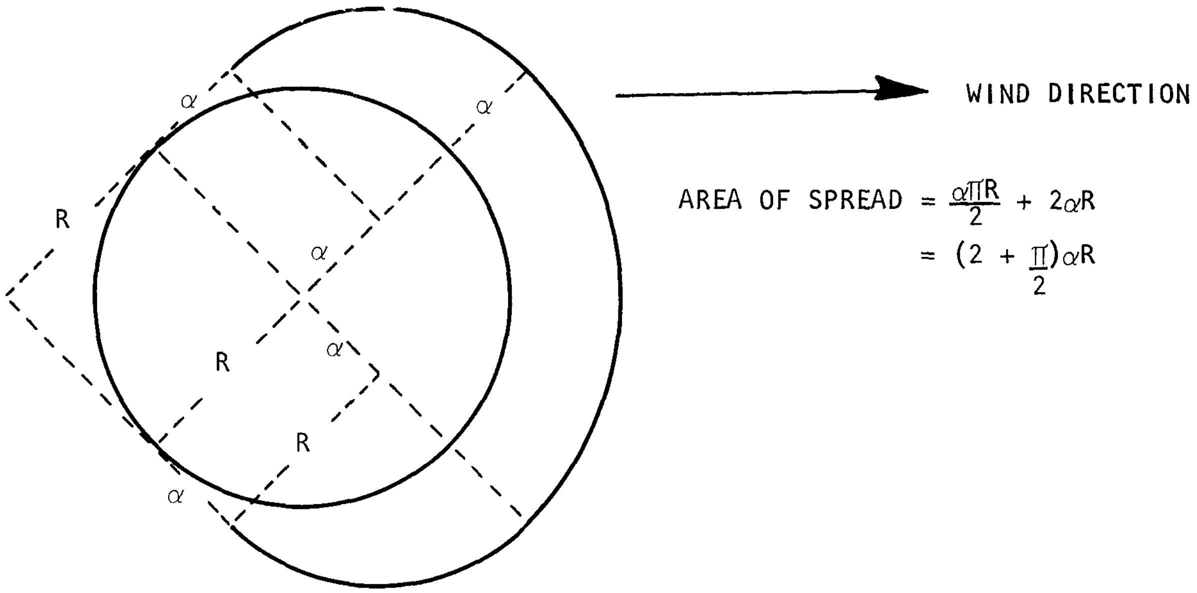


Table 2-6

Ignition and Fire Spread Under Alternative Circumstances

	1 MT				10 MT			
	R(mi)	α(mi)	A(mi^2)	% Spread	R(mi)	α(mi)	A(mi^2)	% Spread
No Spread	3	0	28	0	7	0	155	0
Actionable	8	0.15	207	2	18	0.15	1030	1
Critical	9	1.4	300	17	21	1.4	1515	8.5

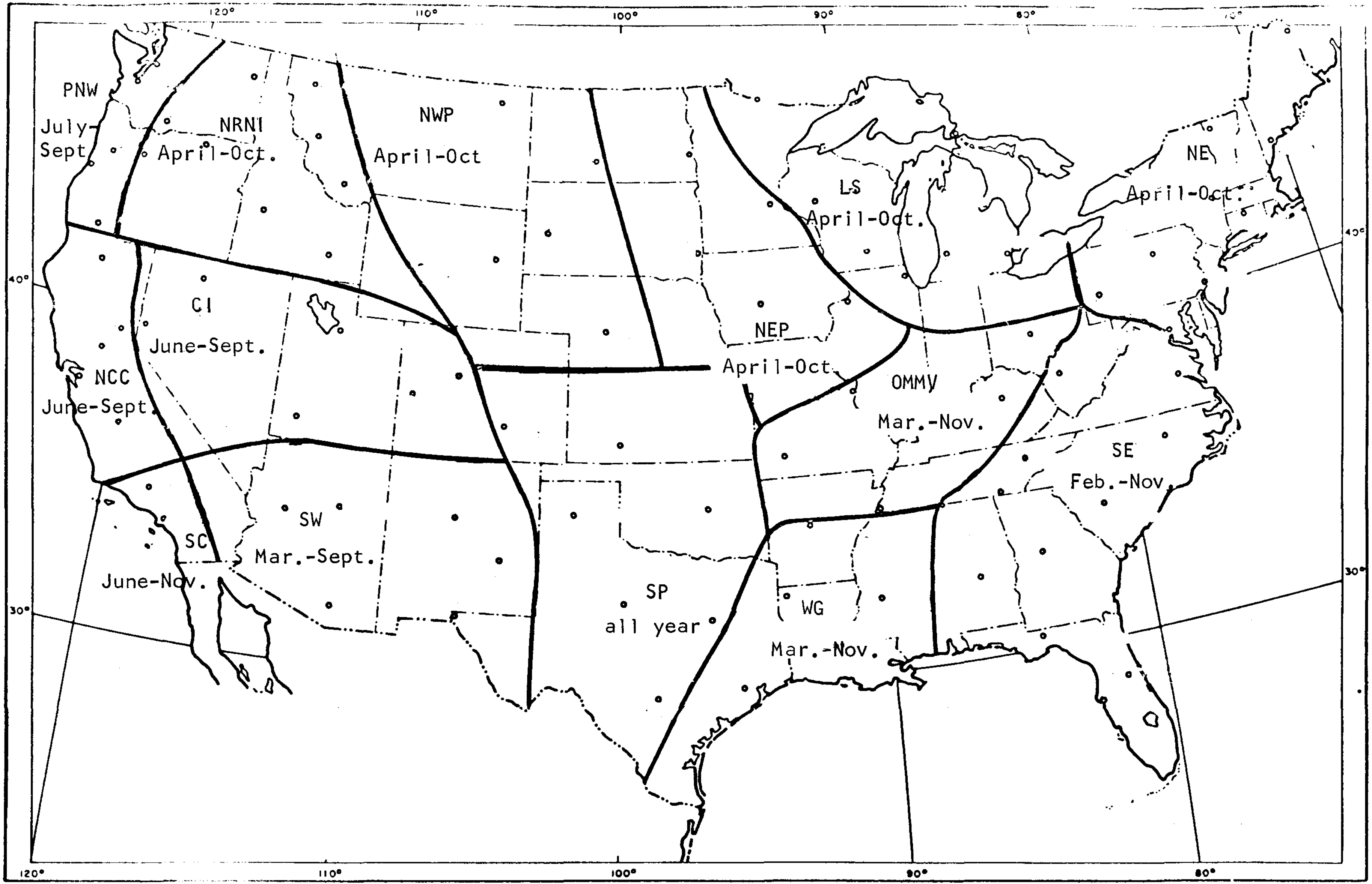
Our various conclusions and judgments to date are summarized in Table 2-6. It can be readily seen that the fractional spread is generally rather small compared with the total area burned, according to the model assumed. It may be argued, of course, that spread from a line source would tend to proceed slightly further, on the average, than spread from a point source, because of the larger number of possible "paths" for the fire to take. However, at least in the "critical" case, this possibility seems unlikely to make much difference, since the fire is assumed to have no probability of going out by itself, and even a fire starting from a point source converts itself into a "line" source after its initial period of spread.

A more important caveat is that the average fire spread in the "actionable" case was calculated on the basis of current statistics, which subsume an effective fire-spotting and fire-fighting capability. In the event of nuclear war this capability might be either degraded or overwhelmed, or both. Fractional spread could, therefore, be somewhat higher than the 1-2% range indicated, although the author suspects that it should remain well below the 7.5-15% range characteristic of fire spread during critical conditions when control techniques are assumed to be ineffective. This conclusion is controversial, however, and may be modified.

A conclusion worth reiterating is that no matter what the source of ignition--lightning, matches, or incendiary attack (whether napalm, phosphorous bombs or thermonuclear explosives)--small fires in forests are not likely to coalesce into mass fires, and mass fires are not likely to spread locally in the absence of those conditions which characterize the seasonal periods of maximum fire dangers. These periods naturally differ for the different areas of the United States (see Figure 2.9). Of course, even during the fire season, there are relatively few days of maximum danger, and the extent of the average hazard may vary considerably in a given area from year to year according to weather conditions. For example, in a recent three-year period several states of the Southwest suffered abnormal dry spells, while during the same period large areas of Texas had excessive rainfall. It is clear, therefore, that no appraisal can realistically assume extreme fire conditions prevailing over large parts of the country at any one time.

FIGURE 2.9

MAXIMUM RISK SEASONS BY REGION



Fire Stations Denoted By ○

4. Conflagrations and Firestorms

A significant characteristic of mass fires is the presence of a large convection column extending thousands of feet into the atmosphere. Consequently, whereas small fires are influenced mostly by surface weather conditions, the direction and spread of mass fires are more influenced by the characteristics at higher altitudes. (For example, embers which are carried up into the column are then transported by the prevailing winds which may be flowing in a different direction and speed from the surface winds.) While it is known that under certain conditions mass fire spread is fairly independent of surface wind speed, there is not yet sufficient empirical evidence to fully justify the alternative view that spread is dependent upon upper winds, except in the sense noted above in connection with the spread of burning materials.[19]

The formation of a convection column depends upon temperature and wind speed, plus the efficiency of the fire as a heat source. Convection column characteristics and their influence upon fire spread provide some foundation for the view that the characteristics of mass fires resulting from nuclear attack might be similar to those of mass fires of the past, assuming similar fuel, weather, and topographic conditions. A mass fire of about a mile in diameter can produce a convection column up to 25,000 feet in height. Since about 70% of the atmosphere lies below this altitude, it has been argued, the fire is thus "infinitely" large and its behavior will be, in many ways, essentially the same as that of a fire a thousand times larger.[20]

A conflagration is a mass fire which moves along the ground as a one-dimensional front under the influence of natural winds, with a moving convection column tilted to leeward ahead of the fire. The higher the ambient wind velocity, the more the column "leans" and the more firebrands are scattered upon fresh combustible material. Since a conflagration tends to spread until it reaches a firebreak or is affected by a change in wind or humidity, the result is that it can burn over a very large area. A special category of conflagration is the so-called "catastrophic" fire, a term applied to fires which burn over areas of 150 square miles or more. As we will see from an analysis of historical examples, very extreme and unusual weather conditions are associated with such fires. The method of original ignition is probably not important in these cases.

The temporal burning pattern for conflagration-type fires is fairly standard (see Figure 2.7).[21] Typically the period of maximum burning is fairly short, followed by a more or less extended cooling-off period. The permanent damage done, e.g., to life forms beneath the soil surface such as seeds, spores, eggs, grubs, etc., depends on the length of time a high surface temperature is maintained.

Clearly it makes some difference whether the peak temperature phase is short, followed by a long, relatively cool, period of smouldering, or whether most of the fuel is burnt in the active period, followed by a rapid cool-off. Table 2-3 shows how typical fuel types normally behave.

Note that the heavier the fuel, the greater fraction of the total energy is released under relatively cool conditions which would not result in serious damage below the surface, so that damage does not increase quite linearly with fuel weight.

A firestorm differs from a conflagration in that a massive vertical and stationary convection column is formed which draws surrounding air from all points of the compass into the fire area. The rate of burning (i.e., removal of oxygen) combined with expulsion of hot air and gas up the convection "chimney" is such as to cause inrushing winds of near-hurricane intensity around the perimeter. The fire literally creates its own weather. After the fire raid on Leipzig in World War II, a wind velocity of 34 miles per hour was reported at a weather station two and a half miles from the edge of the fire. This wind velocity apparently increased rapidly as one neared the fire perimeter.[22] Since, except for gusts, the winds tend to blow concentrically toward the center of the fire, there is likely to be little fire spread beyond the area originally affected. The World War II firestorms, Hiroshima, Hamburg, and Dresden, generally burned less than the area originally ignited.

Several relatively special conditions are probably required for a firestorm to result from a nuclear attack: a large number of ignitions within the area, relatively flat terrain, light winds, and a fairly uniform dense distribution of combustible materials. There is probably no lower limit on size, contrary to what might be expected. Forest service personnel claim that small firestorms occur fairly regularly in conjunction with forest fires, i.e., in localized areas. The maximum size of a firestorm may (or may not) be limited. To set a more quantitative set of criteria would require a deeper analysis than any which has been done to date.* The theoretical difficulties may be inferred from the consideration that the first-order interaction between burning conditions and weather which is applicable to conflagrations is clearly inadequate in the present case. As we have already remarked, the firestorm essentially creates its own weather, which implies a higher order relationship of the form:

$$\text{weather} \longrightarrow \text{burning conditions} \longrightarrow \text{weather}.$$

In familiar terminology, such a relation is intrinsically non-linear. Except for a few fortuitous mathematical models which can be solved exactly, non-linear problems are extremely intractable in general because one's usual approximation methods either have an excessively narrow region of validity or fail altogether.

We would conjecture--although it would be hard to find definite confirming evidence--that one difference between a firestorm and a conflagration is that the "forced draft," characteristic of the former, would result in more complete fuel consumption during the violent phase of burning, and consequently greater long-term damage. This is one respect in which a firestorm produced by a nuclear explosion might differ significantly from a conflagration or catastrophic fire from natural causes. The possible biological consequences of this, discussed later (Chapter IV, section 6), may be quite important, however.

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*T. Lommasson of Dikewood Corporation is currently attempting to develop such a treatment. His results are, unfortunately, not yet available.

5. Past Experience

Forest fire experience of the past provides the only relevant major criterion we can apply to the problem of estimating the thermal effects of nuclear war. Table 2-7 summarizes forest fire experience in the continental United States for the period 1926-59.[23]

Table 2-7

Forest Area Burned Annually and Numbers of Fires in Continental United States

Period	Average Area Burned (sq.mi.)	Maximum Area Burned (sq.mi.)	Minimum Area Burned (sq.mi.)	Average* No. of Fires	Maximum* No. of Fires	Minimum* No. of Fires
1926-36	65,000	81,000	38,000	161,420	226,285	91,793
1937-47	39,900	52,800	25,900	188,438	232,229	124,728
1948-58	16,000	25,900	5,125	157,268	208,400	83,391
1957-59	5,340	5,570	5,125	95,241	104,422	83,391

Organized cooperative efforts by government, state and local authorities and private organizations to prevent and fight wildland fires only began during the first decade of this century and did not reach a high degree of effectiveness until the late '30's. By 1959, 94.7% of the forest land in the continental United States had organized fire protection. The effect of this is very apparent in the above table. During the period from 1926-1936, organized fire protection was not so widespread: 65,000 square miles of forest area burned annually on the average, while in the last period of high protection this was reduced to 5,340 square miles per year. For the period from 1926-1936, fire fighting had less influence on the annual burn rate. The differences from year to year in any period are probably due almost entirely to weather variations, as these affected burning conditions. The lowest annual burn area, 38,000 square miles, was in 1926, while each of the years 1930 and 1931 account for 81,000 square miles. Hill has suggested that this two-year period is perhaps the most pertinent for estimating the effects of weather conditions alone on the extent of fire caused by nuclear attack, since no other variable changed significantly during the decade. From this we arrive at the conclusion that the range of damage from a nuclear attack of given size would vary by a factor of two or so from the best to the worst years.[24] This is not quite germane, however, since an attack would presumably occur on a particular day when the weather pattern would not in fact be average, and the worst case for a single day may be much more extreme than the worst seasonal average.

An even more significant index is the historical incidence of "catastrophic" fires. It is usual practice to reserve this term for fires which spread over areas of 150 square miles or more. Since 1825 there have been 12 great catastrophic forest fires in the United States. In the period from 1825-1910 there were eight great fires which burned areas varying

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*In recent years the number has been pushed up by improved reporting of very small fires which tends to make the figures for successive decades hard to compare.

Table 2-8

Historical Incidence of "Catastrophic" Fires

Area	Dates	Cause of Ignition and Spread	Area $Mi.^2$	Combustion Energy Released (MT)
Eastern Wisc. (Peshtigo) & Central Mich.	Oct. 8, 1871	Merging of many small logging fires; long drought, high winds	5900	300
Miramichi (New Brunswick) & Maine	Oct. 7, 1825	" " " " " " "	4700	240
Idaho	Aug. 10-21, 1910	" " " " " " "	4700	240
Ft. Yukon, Alaska	1950	--	2500-3500	130-180
Wisconsin & Hinkley, Minn.	Aug.-Sept., 1894 Sept. 1, 1894	" " " " " " " "; but moderate winds	2000-3000	100-150
Yacoult-West. Washington & Oregon	Sept. 12-13, 1902	"; but moderate to strong winds. Over 110 separate large fires.	1500-2000	75-100
E. Michigan	Sept. 1-5, 1881	"; but only moderate winds. Some lightning fires.	1500	75
Adirondacks, New York	Primarily May 28-June 3, 1903	Merging of fires from campers, incendiaries. Dry spring; strong winds.	1000	50
Tillamook, Oregon	Aug. 14-25, 1933	2 ignition points; long drought. Fire burned slowly until hot gale force winds on Aug. 24-25.	486 (420 $mi.^2$ in 20 hours)	24
Maine (Mt. Desert Island)	Oct. 1957	" " " " " " "	375	19
Maine	Oct. 21-25, 1947	Long drought, many small fires, low humidity, high winds (50 fires burning).	320	16

250 square miles to 5,900 square miles each. Since 1910 there have been four fires which have burned over 156 square miles to 469 square miles per fire. Table 2-8 gives pertinent details on these fires.[25]

The relative rarity of catastrophic fires is due to the fact that very special conditions must occur in juxtaposition for them to be possible: typically, extended drought, a hot dry spell with low humidity, followed by high winds.

It is worth noting, by the way, that none of these fires was brought under control in the first instance by human fire-fighting efforts, but by natural barriers such as lakes, rivers, and deserts or by changes in the winds. However, the average area burned in such fires has decreased over the years. There are several reasons for this, including improvements in silviculture and more firebreaks because of the clearing of large areas of the forest for agricultural and other purposes as the country becomes settled. These factors obviously have a bearing upon the probability of the occurrence of catastrophic fires, the number of such fires, and the degree of burned-over area in the event of nuclear war. As Hill also points out, there must have been numerous fires in the period before the European immigrants came to this country. If there had not been natural barriers, weather changes, firebreaks, etc., to stop the spread of fire, most of the country would have been burned over in the pre-civilized era.

In summary, the occurrence of catastrophic fires is not likely to be a function of ignition sources, be they natural causes such as lightning or events such as nuclear attack. Very extreme weather and fuel conditions must exist and these, as noted, are rare.

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16. C.C. Chandler, personal communication.

17. H.A. Simon, *Models of Man*, New York: John Wiley & Sons, Inc., 1957, Chapter 9.

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19. Craig C. Chandler, U.S. Forest Service Research Note PSU-N22, 1963, p.2.

20. Chandler, Storey and Tangren, *op*. *cit*., pp. 2, 15.

21. *Ibid*., p. 22.

22. A. Broido, "Mass Fires Following Nuclear Attack," *Bulletin of the Atomic Scientists*, December 1960, p. 410.

23. J. Hill, *Congressional Hearings, Civil Defense*, 1961, p. 353.

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CHAPTER III

ATMOSPHERIC EFFECTS

A discussion of the atmospheric effects of a large nuclear attack can logically be divided into (1) short-term interactions in the troposphere, (2) the effects (possibly lasting for years) resulting from disturbances in the stratosphere, and (3) indirect physical effects on the micro-climate of the surface (especially water economy and erosion) and interactions between the micro- and macro-climate. The latter are mostly reserved for Chapter IV.

1. Tropospheric Effects

Because of rapid mixing and scavenging by wind and rain, debris from nuclear explosions has only a short residence time in the troposphere, measured in days, or weeks, at most. After the larger fragments (local fallout) settle to the ground the only source of contamination is the comparatively slow trickle of fine dust particles from the stratosphere above. Hence, meteorological effects of appreciable magnitude are likely to be limited in duration and, therefore, limited in terms of capability to cause long-term damage.

The most obvious possibility is that changes in weather patterns might arise simply because of the quantity of heat dissipated in the atmosphere by nuclear explosives. The amount of kinetic energy involved at a given moment in a typical great hurricane is equivalent to roughly 170 MT's* (see Appendix E), which suggests on a simplistic energy comparison basis that a nuclear war involving 3000 MT's, half of which is dissipated in the air, might produce some meteorological consequences. On the other hand, single airbursts of weapons in the range of 10-50 MT's have not, in practice, triggered any storms or other meteorological events. This negative result was in accord with the expectations of meteorologists at the time, although one could not have ruled out all other possibilities a priori.

The major ways in which nuclear weapons detonated in the atmosphere might influence weather are (1) by selectively increasing vertical mixing (convection), and (2) by modifying the precipitation mechanism.

The first is suggested by the fact that the fireball of a nuclear explosion heats and entrains a large cubic volume of air, which rises until it expands and cools adiabatically to the temperature of the surrounding air. As the air mass rises, it eventually (depending on initial humidity) cools to the dew point and water vapor condenses to form clouds, releasing a considerable amount of latent heat of condensation in the process. Thus the process of cooling with altitude slows down and follows a much steeper curve (see Figure 3.1) until it intersects the temperature profile curve of the surrounding atmosphere. At this point the temperatures are equalized and the air mass ceases to rise.

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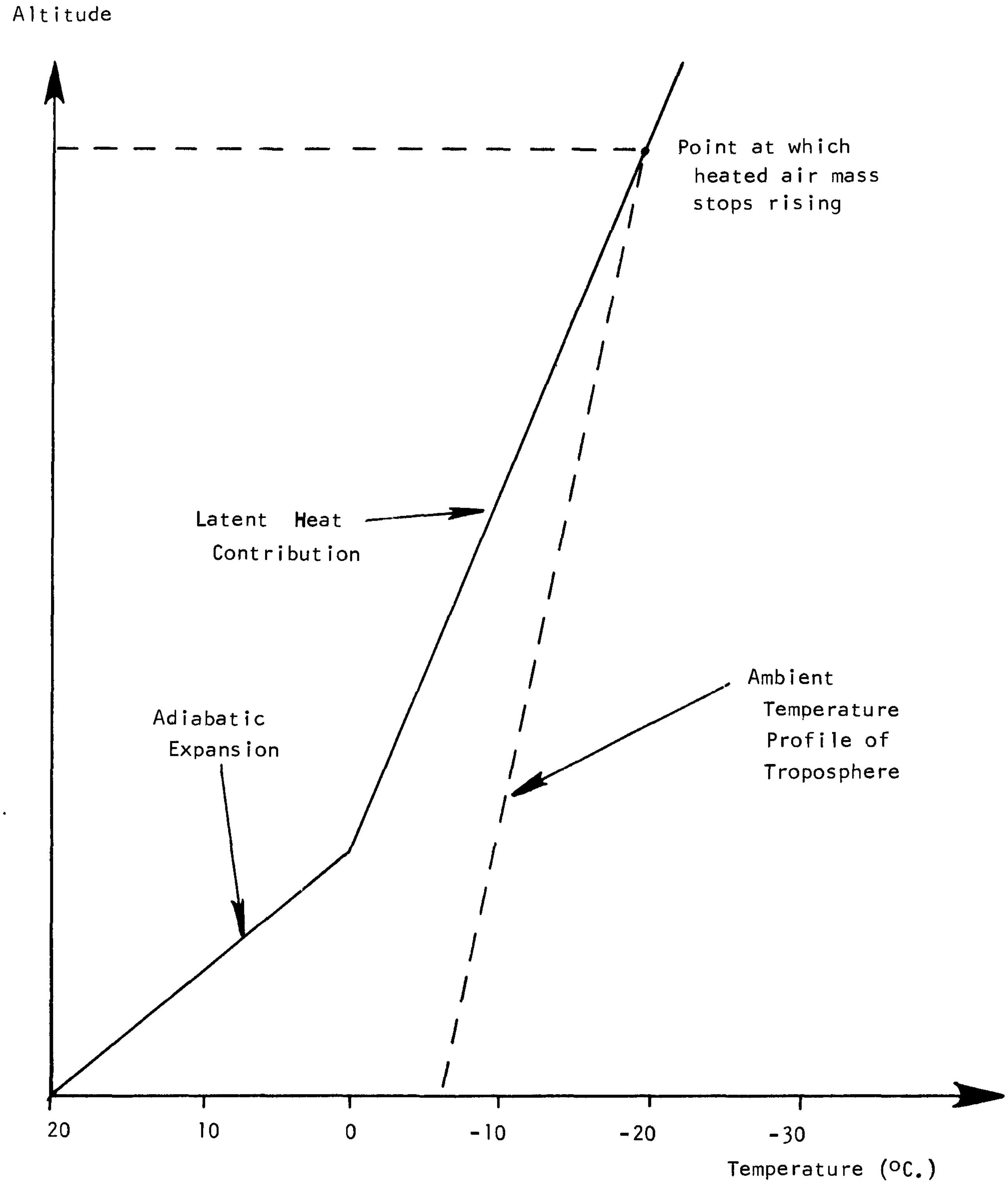
*Total energy dissipated over the hurricane's lifetime may be much greater, but a reliable number is extremely hard to estimate.

FIGURE 3.1

ALTITUDE VERSUS TEMPERATURE OF HEATED AIR



The amount of air which can be raised by 1 MT from ground level to the tropopause is probably of the order of 5×10^{13} cubic feet, or ~ 500 cubic miles.[1]

A nuclear war involving 3000 MT's of nuclear explosives might therefore result in lifting something like 1,500,000 cubic miles of air. This would effect a substantial, if temporary, enhancement of the normal rate of turbulent heat transfer between the surface of the earth and the atmosphere. The results seem likely to be twofold. In the first place, some of the condensed moisture might come down as rain, at least to the extent that other essential preconditions for precipitation, e.g. freezing nuclei, are present. Second, and more important, the temperature profile of the troposphere might be altered for a time.

The characteristic pattern of thunderstorms is excess heating at the surface of the ground, compared with aloft, which creates vertical instabilities (updrafts) and violent turbulence, often accompanied by heavy rain. As long ago as 1839, James Espy suggested that brush could be burned in periods of drought to stimulate convection and cloud formations.[2] The idea has been tried and found promising in equatorial Africa in recent years.[3] The Esso Research & Engineering Company has suggested that asphalt-paved areas of sufficient size in selected tropical regions might stimulate rainfall. Forest fires and firestorms have also occasionally been observed to produce rain.

In addition, however, much of the heat produced by the nuclear explosions themselves, plus a large contribution of latent heat of condensation, plus the heat content of the lower air (previously in thermal contact with the ground) would all be carried upward where they would tend to increase the temperature at the top of the troposphere. In some cases temperature inversions might occur, but more generally the result would probably be that thermal radiation from the atmosphere would increase to counterbalance the rise in temperature. Much of this energy would ultimately be lost to space, rather than returned to the lower atmosphere. Moreover, the upper troposphere would presumably be cloudier than usual, because of the above-mentioned condensation, resulting in increased reflection of solar radiation and, at the same time, more effective absorbtion and reflection of outgoing thermal radiation from the earth. The balance of the latter two factors would probably depend on latitude: in polar regions where solar radiation (per unit area) is weak because of the nearly horizontal incidence, clouds would lead to net warming of the lower atmosphere; in the tropics the reverse might be true. On the average, however, clouds are more effective at preventing thermal radiation from escaping than in excluding solar radiation (similar to the "Greenhouse Effect"). This would mitigate the over-all heat loss.

Qualitative considerations suggest that, on balance, the lower troposphere, and the surface of the ground, would be substantially cooler and drier for some time (weeks) after the detonation of a large number nuclear weapons, while the upper troposphere would be warmer and cloudier. There would, in all likelihood, be some net loss of heat into space, the amount depending on the detailed balancing of the various factors.

Specialized instances of possible consequences of vertical instability such as the possibility of "venting"--punching a hole through a semi-permanent inversion (e.g., over Los Angeles) are not of significant importance for our present considerations, since the requisite conditions are not widespread. The possibility of producing heavy rain as a result of low thermonuclear bursts over water can be dismissed also, since the quantities of water evaporated are not impressive. For example, 1 MT or 10^{15} calories is sufficient to evaporate 2 x 10^9 kg. of water--which would yield only 1/5 of an inch of rain over a 200-square-mile area.[4]

It has also been suggested that cyclonic storms (e.g., hurricanes) might be deliberately modified by using thermonuclear explosives.[5] One method would be to change the direction of the storm's path by modifying the symmetry of the storm pattern. The second would be to remove a portion of the warm air in the eye of the storm by induced upward convection, thus "cooling off" the storm both literally and figuratively.

The second technique appears slightly more promising, but both are completely hypothetical. The relevance of either possibility to a post-nuclear attack situation seems almost nil, in any case.

Modification of the mechanisms responsible for precipitation is another interesting possibility. It is thought, currently, that two different basic mechanisms are operative. The first, suggested by T. Bergeron (1933)[6] and confirmed by W. Findeisen (1938),[7] is essentially that in supercooled regions of high clouds (e.g., cirrus) ice crystals are formed, and that these are "hydrophilic," i.e., they tend to grow at the expense of water vapor in the surrounding region, which reduces the ambient humidity and causes droplets of liquid water in the vicinity to evaporate. In suitable circumstances these ice crystals can grow fairly large and start to fall rapidly toward the earth. Usually, as they enter warmer regions of the atmosphere, they melt and arrive as rain. Methods of artificial rainmaking, initiated by Langmuir, Schaeffer and Vonnegut of General Electric,[8] depend on injecting simulated ice crystals, e.g., silver iodide or dry ice, into supercooled clouds. A theory has been advanced that dust particles sifting down through the stratosphere play a similar role in nature. Periods of maximum precipitation have been found to be correlated surprisingly closely with meteorite showers, i.e., passages of the earth's orbit through clouds of interplanetary dust, allowing for a delay of 30-31 days between the date of "seeding" of the top of the atmosphere and the peak rainfall periods.[9]

Between 10^7 and 10^8 tons of meteoric dust (of all sizes) enter the top of the atmosphere annually. This is comparable to the amount of debris which would be lifted (on the basis of .75-1 ton of material per ton of explosive)[10] by 10-100 MT's of thermonuclear explosive, detonated on the earth's surface. Several types of clay soil, including kaolinite, have been found to be comparable to silver iodide in ice-nucleating effectiveness.[11] The presence of too many potential nuclei may have an adverse effect, however. as the optimum concentration appears to be of the order of 1-10 particles per liter. If more are present the resulting ice crystals may not be able to grow large enough (i.e., fast enough) to fall. On possible consequence of a larger nuclear war, e.g. 1000 MT's and up, would be to reduce normal precipitation by "poisoning" the atmosphere with an excessive number of potential freezing nuclei.

The other mechanism known to be involved in precipitation, especially from warm clouds, is colloidal instability. For reasons not well understood, droplets in warm clouds can undergo a relatively sudden process of coalescence and aggregation, and fall as rain. This phenomenon cannot be explained by condensation and random collisions of droplets alone: the collision frequencies for reasonable water content and turbulence are too low to account for the growth of raindrops in the observed time of onset, unless one postulates extremely long trajectories within the cloud, i.e., powerful updrafts. The main difficulty is to account for the initiation of the process, which requires a certain number of large droplets. One tentative explanation which has been advanced is that hygroscopic water soluble crystals, particularly salt particles scooped up from the surface of the ocean, tend to collect enough water in which to dissolve themselves. As the salty droplets grow large enough they begin to fall through the cloud, sweeping up other small droplets en route.[12] The larger the drop grows by accretion, the more droplets its path intercepts and the faster it grows. Another suggestion is that the onset of accretion is stimulated or even controlled by the presence of electric fields. It has been shown that coalescence of water droplets is substantially increased in the presence of potential gradients of 200 volts/cm, whereas the normal (fair weather potential) is 1 volt/cm or less.[13] In thundershowers, on the other hand, gradients of 1500 volts/cm have been observed. Several current research programs are actively exploring the role of electric fields in precipitation, notably Vonnegut, et al (Arthur D. Little), E. J. Workman and M. Brook (New Mexico Institute of Mining and Technology). Workman has noted, for instance, that the presence of small amounts of certain trace contaminants (such as ammonia) in freezing nuclei can strongly influence the dipole fields of thunderclouds or even reverse their polarity. Further experiments are in progress.[14]

It is difficult to conjecture to what extent nuclear explosions might influence colloidal instability of clouds, if at all. If the coalescence mechanism is electrical, the presence of charged particles (β-particles) in the radioactive debris might be important. Ionization, even from kiloton explosions in Nevada, has been observed to increase the conductivity of the atmosphere significantly, as far away as the Eastern U.S.[15] The effect of higher atmospheric conductivity would be to reduce potential gradients and charge separation, thereby (possibly) adversely affecting precipitation probability and (very likely) lowering lightning incidence in thunderstorms.[16] It is worth remembering that 70% of all forest fires in the U.S. are kindled by lightning strikes, expecially from "dry" thunderstorms. The noticeable electrical consequences of the radioactive debris from 1000 MT's of explosions might last for a number of years, as long as substantial β-activity remained in the stratosphere, from whence it could trickle down into the troposphere.*

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*Recall that Sr-90, one of the long-lived isotopes which is preferentially distributed among the smaller particles, is a β-emitter.

If an effect exists at all, it is likely to be in the direction of reducing over-all precipitation. However, there has apparently been no measurable reduction in the rainfall which can be correlated with atmospheric tests of nuclear weapons (>200 MT's in all), whence the magnitude of such an effect seems unlikely to be catastrophically large. The evidence is not all in, however: in fact, the northern hemisphere does appear to be undergoing a prolonged drought at present (1965).

Chemical contaminants present in the atmosphere in comparatively minute amounts (e.g., ozone, sulfur dioxide, hydrogen sulfide, methane, etc.) are known to play a role in the radiation balance of the atmosphere. Although many pertinent chemical processes are understood in some detail, the over-all picture is extremely obscure. To the extent that a meteorological problem exists today as a result of such contaminants, i.e., due to atmospheric pollution, the principal cause is presumably large-scale combustion of fossil fuels. The combustion processes themselves are usually somewhat inefficient, so that unburned hydrocarbons and carbon monoxide are released into the atmosphere in substantial quantities. In addition, most commercial fuels have a considerable impurity-level: for example, coal often contains 3% or more sulfur. When natural fuels such as wood are burned, e.g., in forest fires, there will also be organic constituents such as esters, oils and even amino acids in the combustion products. If a nuclear attack should result in a large number of fires, or if the explosions themselves should vaporize a substantial quantity of organic material--which did not occur in any of the nuclear tests--very serious chemical pollution of the atmosphere could conceivably occur. The problems involved would probably be qualitatively different from those associated with peacetime atmospheric pollution: sulfur compounds and unburned hydrocarbons would probably not be major contaminants. On the other hand, nitrogen compounds, organics and various other possibilities might be important. Any further comments on this score at present would be sheer speculation, but some further research might well be warranted.

2. The Stratospheric Effects

In general, stratospheric effects will depend on the quantity of material injected and the distribution of particle sizes. Since the stratosphere can almost be defined as the region "above the weather," there is little vertical air movement and the length of time a particle remains suspended depends on the rate of passage through a viscous medium and is a function of particle size and shape. Particles of a few microns (μ) in diameter tend to remain in the upper atmosphere for times of the order of years, the length of time being greater, the smaller the particles. The computation for an idealized model can be made easily using Stokes' law.* (See Appendix B, Figure B.1) Actually the altitude of the tropopause, which marks the top of the troposphere and the bottom of the stratosphere, increases toward the equator and decreases near the poles. It may approach ground level during a polar winter. Moreover, the isothermal stratosphere per se really only exists between the latitude of the so-called jet stream (roughly the storm

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*Which was originally put forward by Edward Stokes to treat this very problem in connection with the Royal Society study of the Krakatoa eruption in 1888.[17]

track) and either pole. In the "tropics" (i.e. between the northern and southern hemisphere storm belts) the tropopause is higher (~17 km) and there is a rising temperature gradient above it. At high altitudes warm tropical air circulates slowly from the equator toward the poles. The jet streams mark regions where the polar stratosphere and troposphere mix. Furthermore the jet streams move north and south roughly between 20° - 50° according to season, paralleling the polar "front at ground level (See Figure 3.2).[18] They are lower in altitude, stronger and closer to the equator during the winter. Thus to some extent by moving up and down and back and forth the jet stream "vacuum cleans" the lower stratosphere in its seasonal progression; particulate debris caught up by the jet stream is quickly brought to earth by wind and rain.[19]

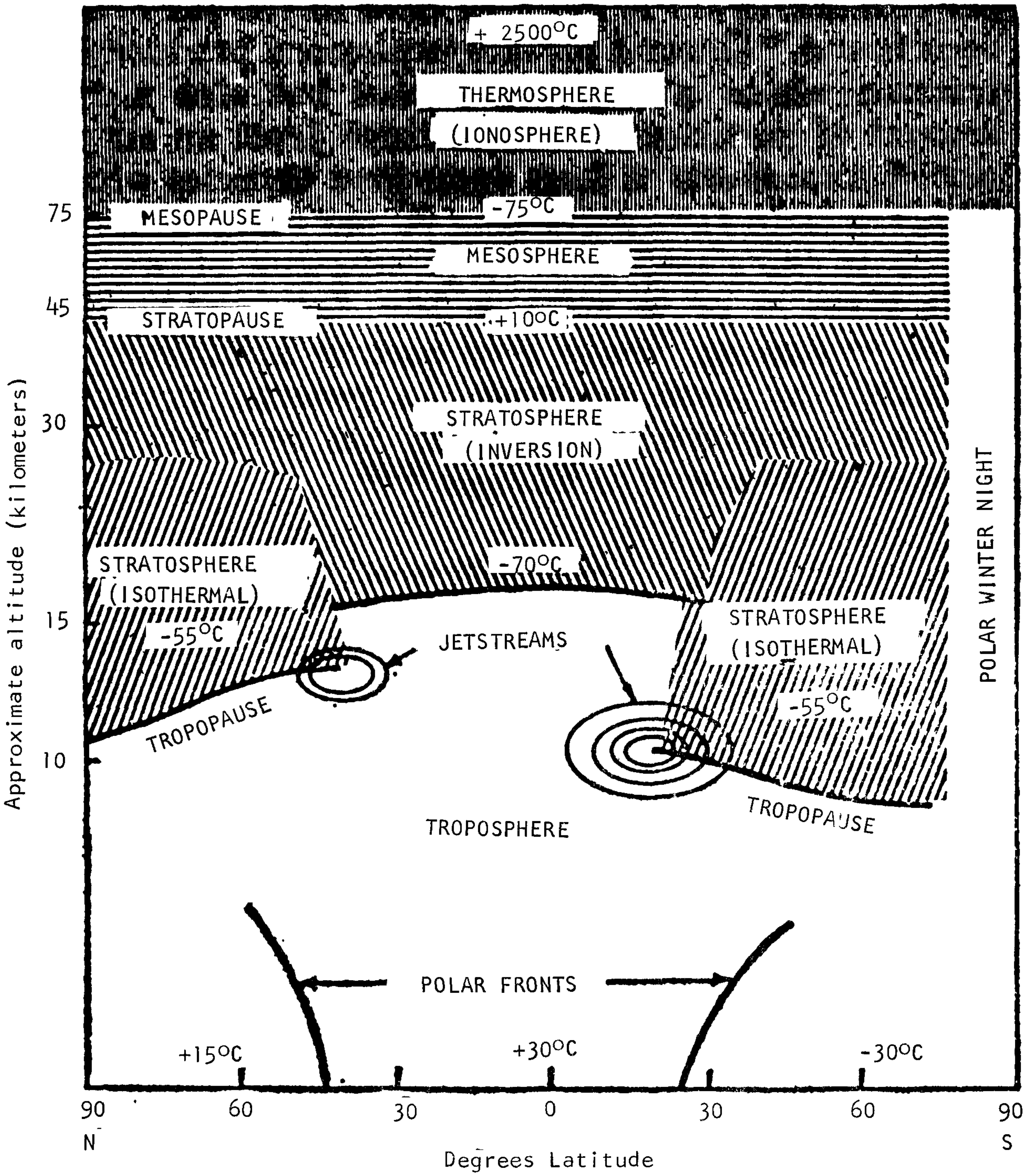
The most realistic estimates we can currently make would assume something like "Stokes' law" behavior above 35,000 feet and a much faster scavenging rate below that altitude depending, however, on season and latitude. Generally speaking, debris comes down faster, the nearer to the north or south pole it is injected. This accounts, incidentally, for the unexpectedly small percentage of stratospheric (world-wide) fallout from the 1958 and 1962 Soviet nuclear tests carried out in Novaya Zemlya (~ 75° N) as compared to the U.S. tests in the tropical Pacific.[20]

It is well known that dust particles suspended in the stratosphere may affect the radiation balance of the earth.[21] Particles of the order of 1 μ or less in radius are relatively efficient scatterers and diffractors of solar radiation, whereas the longer wave (infra-red) radiation from the earth is transmitted efficiently. A layer of small particles is therefore essentially equivalent to a filter which "passes" thermal radiation in the outward direction but interferes with and deflects incoming solar radiation, thus reducing the over-all energy income vis-à-vis outgo and cooling the surface of the earth. Since small particles remain suspended for the longest times, this cooling effect can be expected to result from any process which causes large quantities of dust to be injected into the stratosphere. There have apparently been some historical examples. The huge Tomboro volcanic eruption of 1814 which blew up enough dust to darken the sky 300 miles away for three days[22] was followed by the "year without a summer" in 1816 (New England) during which temperatures in July averaged 7° C. below normal. The three outstanding historic volcanic events, Asamayama in 1783, Tomboro in 1815 and Krakatoa in 1883, were all followed by years of perceptibly cooler-than-average world-wide weather.[23]

This mechanism is quantitatively important enough at first sight to deserve closer attention. Typical volcanic dust absorbs and re-radiates the longer wavelength better than short (solar) ones, and a layer of such particles with diameters greater than, say, 10 microns, would tend to heat the surface of the earth slightly, rather than cool it, similar to the influence of CO_2 ("Greenhouse Effect"). However, very small volcanic dust particles on the order of 1 μ radius tend to scatter the short wavelengths more effectively. The wavelength corresponding to maximum intensity of the sun's spectrum (on an energy scale) is about $\lambda = 1\mu$ (near infra-red) and that of the earth is about 12μ. Since the

FIGURE 3.2

STRUCTURE OF ATMOSPHERE IN JULY



earth's energy "income" from the sun and its energy "outgo" in the form of radiation into space must always be equal (averaged over a period of time) the surface temperature of the earth must adjust so the two are in balance. This process is considered in more detail in Appendix C, where it is shown that any mechanism such as dust in the stratosphere, which reduced the average intensity of received solar radiation by 10% would cause a lowering of the average surface temperature of the earth in equilibrium by 2.5% or 7.5° C.

The connection between an assumed reduction of insolation and surface climate depends on how long the change persists. The above calculation is valid for equilibrium, but the surface of the earth takes quite a long time to reach actual thermal equilibrium--it is difficult to say exactly how long--due to the tremendous (virtually infinite) heat storage capacity in the oceans and the slowness of circulation below the top 600 feet of water. On the other hand, the surface of the land can "relax" fairly quickly by radiating excess heat away (or absorbing radiation in turn), although the interior can only lose heat by conduction or vulcanism--resulting from internal convection--which is an extremely slow process. Thus, rather paradoxically, it appears that a kind of "quasi-equilibrium" may be achieved relatively quickly.

W. J. Humphreys has made a simplistic calculation of insolation reduction based on the assumption that the particles are monodisperse non-absorbing spheres of some glassy substance with an index of refraction m = 1.5 and radii equal to 0.92 μ. The calculation is further based on the fact that most of the sun's spectrum consists only of wavelengths short enough so that Fresnel scattering can be assumed. With these assumptions the intensity of light passing through the dust layer is found to fall off as $\exp(-\gamma x)$ where x is the path length in centimeters and γ is an attenuation coefficient equal to

$$\gamma \cong 2\pi a^2 \rho_o \times 10^{-8} \text{ cm}^{-1}$$

where a is the particle radius (= .92μ) and ρ_o is the number of scatterers per cubic centimeter.[24]

Using the above results it is possible to deduce that a 20% reduction in insolation in the north temperate zone (where the angle of incidence of the sun's rays is such that path length through the dusty layer is twice the vertical thickness of the layer) could be accounted for by about 1.7×10^{24} particles distributed uniformly around the earth. The thickness of the dust layer is essentially irrelevant. Only 5.75×10^{-3} km^3 of material would be needed to produce this number of particles. In terms of weight, assuming a density of 2 gm/cc., it amounts to 11.5×10^6 metric tons.

The initial particle-size distribution of fallout particles produced by nuclear explosions is not well established, but a brief discussion of the current state of (unclassified) knowledge is given in the first section of Chapter I. The distribution of particle sizes actually in the stratosphere at a later time is quite another matter anyhow. The larger particles fall rapidly while the smallest may stay aloft for years. Assuming a polydisperse initial distribution, the distribution as a function of time will therefore have a maximum which corresponds to smaller and smaller particles as time goes on. The Bishop's rings (diffraction patterns around the sun) which Humphreys cited to justify his assumption of $r = .92\mu$, might have corresponded merely to the "peak" of the residual distribution at the time of the observations. Time-dependent calculations using several log-normal distributions are exhibited in Appendix B. The implications for the earth's thermal balance are explored in Appendix **C**.

A glance at the magnitudes involved makes it quite clear that the critical uncertainty is the fraction of the mass of the debris of nuclear explosions in the effective size range $0.3 \leq r \leq 3\mu$. If the results of Appendices B and C have any general validity, then less than .1 mi^3 of material,* spread over the above range of sizes, would suffice to produce an average 20% decrease in isolation (i.e., $e_1 \cong .2$) and a 5% decrease in average absolute temperature.

For purposes of argument it can be assumed that 10^4 MT's groundburst would lift (into the stratosphere) 1 cubic mile of debris with a specific gravity of about 2 gm/cm^3 into the stratosphere. If 1% of this amount remained for a year, it would result in a 2% decrease in insolation at the specific time. If only .1% survived, it would take ten times as much dust (10^5 MT's), and so forth. The "survival-rate" clearly depends, in turn, on the original particle size distribution, which depends, in turn, on the source or the mechanism by which the particles were produced. The most critical case (from the environmental point of view) is presumably that of a monodisperse or strongly peaked particle size distribution clustering around $r \cong .3$ to $.5$ microns radii and initially injected very high in the stratosphere.

The eruption of Krakatoa (1883) offers some illuminating comparisons. One year after the explosion the average of all pyrheliometric readings (entirely in the northern hemisphere) recorded a 13% reduction of insolation.[25] Since Krakatoa is 9° south of the equator, the bulk of the ejecta must have stayed in the southern hemisphere. Hence a world-wide average reduction closer to 20% probably occurred. On the basis of the scattering analysis, it would appear that a volume of dust of the order of 0.1 cubic mile must have remained in the stratosphere at least a year. Even assuming the initial injection was extremely high (150-200 Kilofeet)** allowing a longer time for settling, relatively few particles greater than 1μ in radius would have been left at the end of a year (see Appendix B, Figure B.1). Calculations from observations of optical phenomena, e.g., "Bishop's rings," led to the estimate $r = 0.92\mu$.[27]

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*Depending on the exact distribution.

**The column of ash during the main sequence of explosions, 1:00 p.m., August 26th to 10:00 a.m., August 27th, rose 26 kilometers or more. After the final cataclysm the column was observed to be 80 kilometers high.[26] The accuracy of the observations is open to considerable question, of course, and some meteorologists are inclined to dispute them very strongly.

The actual amount of material ejected from Krakatoa is estimated by vulcanologists to have been about 5 mi^3,* which implies that somewhere in the neighborhood of 1 part in 50 (by volume) consisted of particles $< 1\mu$ in radii. This is consistent with the notion that "new" volcanic ash may be somewhat coarser than the finest ("oldest") weathered soils, i.e., clays. On the other hand, volcanic ash is presumably not too dissimilar to fallout.

The feasibility of injecting a sufficient quantity of suitably fine dispersoid into the stratosphere to cause perceptible change in the weather is not in serious dispute. It has been discussed, even in connection with possible deliberate weather modification schemes.[28] The question of what the ultimate consequences would be, if any, is more uncertain.

The reduction of insolation would not be uniform, for various reasons. Initial distribution would certainly not be uniform: the northern stratosphere would probably receive three times as heavy a load of dust as the southern (based on the planetary distribution of Sr-90). Further, the tropopause is higher in the tropics, whence stratospheric dust will tend to be scavenged out more quickly. Finally, the further north one goes, the more nearly horizontal, hence longer, would be the path of the sun's rays through the dusty layer. Hence the incremental reduction of insolation would be an increasing function of latitude, e.g., if solar income were cut 2% at 45° N., it might be down only 1% at the equator and 5% at the North Pole. The temperature reduction at the surface might or might not be correspondingly greater in the far north. On balance, however, the temperature differential (i.e., gradient) between tropics and arctic would probably be increased.

To compensate for the temperature gradients which normally exist between polar and equatorial regions, convection currents must flow both in the ocean and in the air. One of the principal mechanisms for the northward flow of heat is evaporation and precipitation of water. Tropical oceans give up heat by evaporation; northern air masses recover the latent heat as the water vapor condenses in the storm belt. Hence a steeper temperature gradient between the tropics and the poles would presumably (other things being equal) result in greater precipitation in northern latitudes. Of course "other things" are not necessarily equal; as is pointed out in Appendix C, there may be an over-all drop in heat transfer between the earth and the atmosphere, which could be accompanied by lower average humidity and lower evaporation rate. This factor would tend to operate in the other direction. The net result of the kind of situation we are discussing, namely a greater reduction in heat income in the arctic regions than at the equator, would very likely be increased turbulent mixing in the temperate zone, but with somewhat less certainty of an increase in precipitation.

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*Again, the confidence-level attached to this figure is very low, since there are serious disagreements as regards method of calculation, etc.

Nonetheless, historical evidence, such as it is, seems to support the theory that a drop in average temperature would be accompanied by greater precipitation over the northern land masses. A self-perpetuating cycle could then be set in motion: greater snowfall in winter, followed by cooler summers, would cause snow lines to creep downward year by year.[29] It happens that snow and ice are highly efficient reflectors of solar frequencies, but are quite transparent in the infra-red region of the spectrum.* Hence, a higher percentage of the sun's heat is reflected (in the north), while the earth's thermal radiation is still transmitted through the mantle of snow and ice and continues to be (partially) lost into space at almost the same rate as before. Thus a lower local equilibrium temperature is established which tends to increase the meridional temperature gradient, resulting in still greater storminess, greater precipitation, and an acceleration of the process. Of course, there must be a countervailing mechanism. A likely possibility is that, as more and more water is trapped as ice and snow so that sea levels drop and evaporating surface decreases, the over-all vertical temperature gradient decreases because of the cooling of the earth, the rate of evaporation decreases to the point that ice and snow accumulation ceases, and the process begins to reverse itself: each summer a little more melts than the year before, etc. It has been suggested by M. Ewing and W. Donn[30] of the Lamont Geological Observatory that the freeze-up of the land-locked Arctic Ocean, at the lowest point of the glacial cycle, may account for a sufficient reduction in evaporating water area to start the pendulum back in the other direction. However, there is, at present, no theory of glaciation which is sufficiently generally accepted to base firm conclusions on. The most that can be said is that expert opinion does not dismiss the notion than an artificially induced cold spell could kick off a new ice age.

It has been estimated that the average world-wide temperature during the last glacial epoch was 3-4° C. lower than it is today. A 1° C. average annual temperature difference corresponds to roughly 200 meters in altitude and 1.8° of latitude (~ 125 miles).[31] (See Figure 3.3)[32] The consequences to crops could be perceptible. For example, winter wheat in the Pacific Northwest requires about 1900 day-degrees (measured in Fahrenheit above 40o)[33] to ripen. A decline in average temperature of 1° C. (~ 1.8° F.) would produce a deficit of 220 day-degrees by the time ripening normally occurs--enough to delay the harvest a full 10 days and allow time for insects, birds, and disease to take a heavy toll. There are many uncertainties in this type of calculations (as in others we have made). Fluctuations of this magnitude have probably occurred in the past century (for other reasons) and the worst situation might be one in which a natural cold spell was magnified by the type of effect under discussion.

The influence of temperature on rate of plant growth and evapotranspiration has been summarized by Thornthwaite.[34] The curve in Figure 3.4 is based on an empirical equation relating growth-rate and temperature, in which the parameters are fitted to data for maize seedlings collected by Lehenbauer.[35]

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*Water (in any form) is opaque to infra-red radiation between about 5.5 and 8μ, and nearly opaque at wavelengths longer than about 19μ. Between 8 and 19μ there is a reasonably clear "window"; this corresponds to the peak region of the IR spectrum.

FIGURE 3.3

RANGE OF AVERAGE ANNUAL MINIMUM TEMPERATURES (°F)

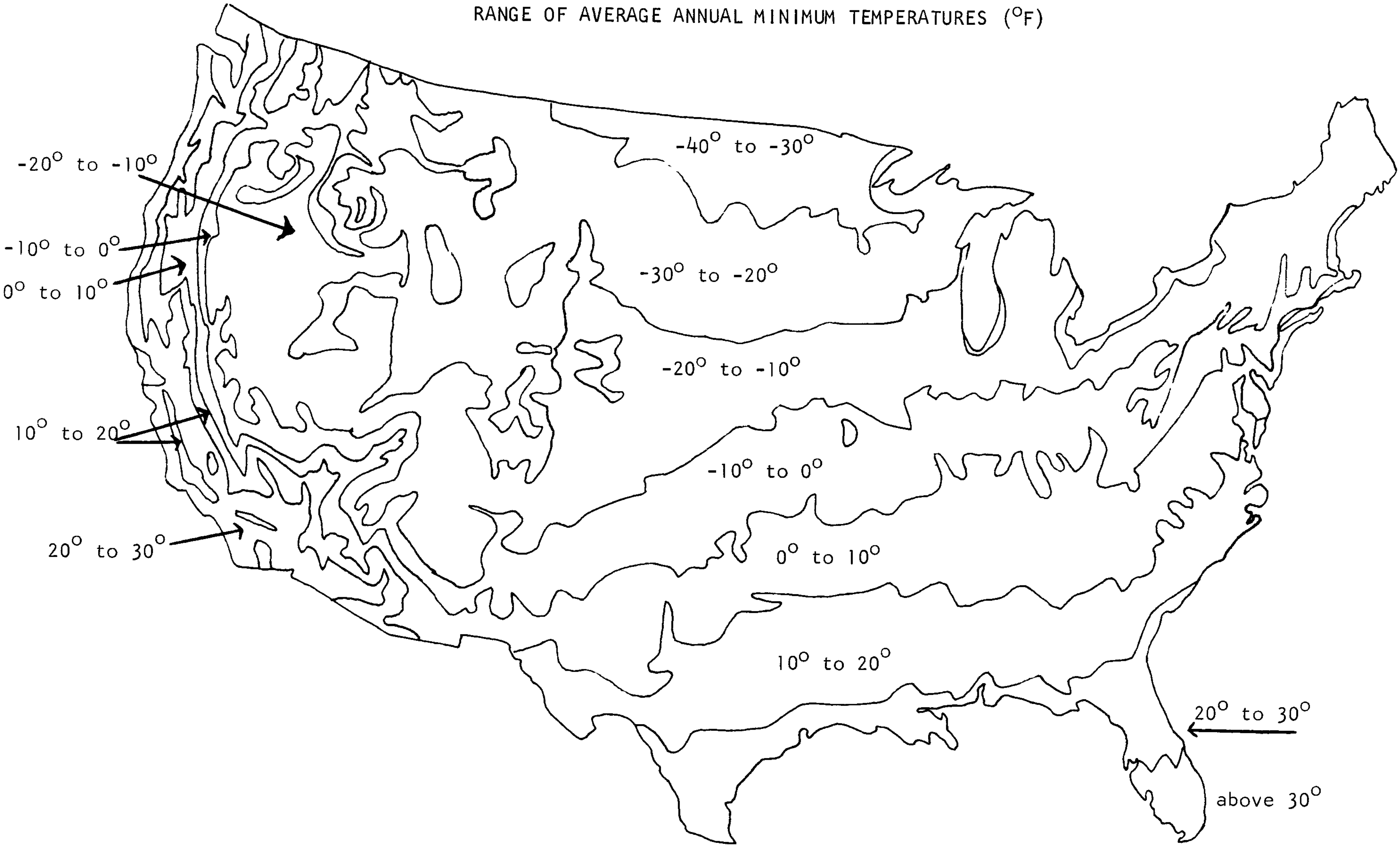
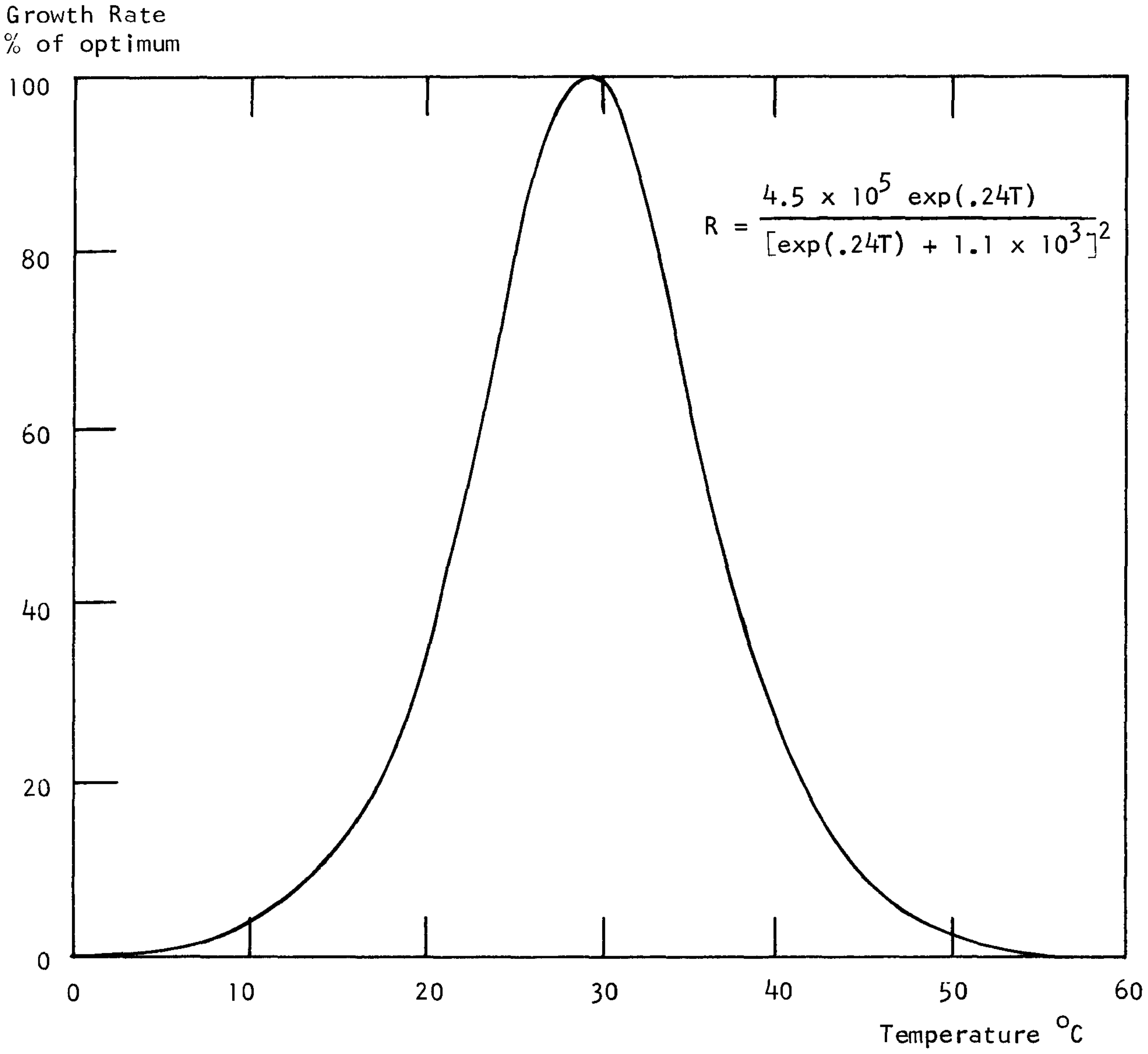


FIGURE 3.4

CORN GROWTH AS A FUNCTION OF TEMPERATURE



Other possible biological consequences of climatic disturbances are numerous. Insect activity is apparently particularly sensitive to both extremes of temperature and average temperature, as well as humidity. For example, it has been observed that grasshoppers remain relatively inactive and do not fly at temperatures below 77-80° F. The Mormon cricket becomes active only on clear days with air temperatures above 65°F. (and less than 95°F.) and soil temperatures simultaneously in the range 75-125°F. Chinch bugs are relatively inert at temperatures below 70°F. and on cloudy humid days. The Mediterranean fruit fly likes conditions of fairly high humidity (65-75%) and temperatures between 60°F. and 99°F. The Western Pine beetle requires temperatures above 50°F. The catalog could be extended indefinitely. The damage done by insects to crops depends strongly on their degree of activity.

Insect reproduction is probably even more sensitive to temperature and humidity variations, although specific data are scarce. It is known, however, that the number of insects surviving a winter depends strongly on how harsh the weather has been. The northern boundaries of territory infested by some species of insects regularly coincides with a particular isotherm, e.g. the Brown tail moth extends to the -25° F. isotherm. Even in summer, weather conditions often determine the fate of insect populations. A drop of 5° F. in average summer temperature is seemingly enough to reduce the viability of second generation Corn borer pupae from 50-80% to 10% or so. Rather similar observations of temperature dependence have been made on the cotton boll weevil. The Hessian fly, a wheat pest, seems to thrive only in the unusually wet weather, as do sawflies of Dolerus spp.

Plants and diseases thereof are similarly weather-sensitive. Many bacterial plant diseases thrive in warm weather, while fungal diseases typically prefer cool damp weather. However, the resistance of the plant-hosts is also temperature- and humidity-dependent. Crops grow best where the climate is most nearly optimal for them and least encouraging to pathogens. Thus corn is most resistant to blight at soil temperatures above 75° F, while wheat has maximum resistance at 54° F. A change in the meso-climate, e.g. a shift of several hundred miles north or south in the (seasonal-average) soil-temperature, isotherms, could result in drastic increases in vulnerability of many crops to diseases.

The pandemic of potato late blight (a fungal disease) in Ireland in 1845 and 1856--the cause of a disastrous famine and subsequent depopulation--resulted from unusual weather conditions. This disease can spread with explosive speed when circumstances combine to produce a long period of rainy or foggy cool weather early in the growing season. Temperatures of less than 75° F. combined with humidity of 90% or more, maintained for 12 hours or longer, is the worst combination. In Aroostook County, Maine, the largest potato growing area in the U.S., such conditions occur about one year out of two. The appearance of weather favoring blight two years in succession is especially dangerous since there are many overwintering spores of the fungi at the beginning of the second season.

An outbreak of the wheat stem rust is most likely to follow extended damp cool spells in the southern wheat growing regions (moving gradually north as the spores are spread by the wind), followed by hot dry weather at the time when wheat kernels are forming on the blighted plants. This sequence occurred in 1935 and resulted in the loss of 25% of the United States' wheat crop, and 60% of the crop in North Dakota and Minnesota.

There is a great deal of scattered information similar to the examples cited but it is far from sufficient to form any coherent pattern which would permit predictions of specific consequences following from specific climatic perturbations. It does seem reasonable, however, to conclude that the greater the magnitude of the oscillations, the fewer species of either insects or plants will survive in a given location and the more closely confined will each species be to its optimum climatic zone. The greater the extremes of weather, then, the simpler the ecological relationships. Ecosystems involving very few interacting species may also be more unstable, if experience is any guide, than more complex communities. Arid plains, conifer forests and arctic tundra--all simple systems--are all too frequently beset by wild ecological gyrations such as locust or beetle plagues, rat-quail outbreaks, lynx-rabbit cycles, and the like, whereas tropical forests, at the other extreme, appear to be more stable. (The appearance may, however, be deceptive since (1) simple ecosystems have been more intensively studied and (2) tropical population dynamics are less closely tied to the seasonal cycle and may therefore have longer periodicities).

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Chapter IV

SECONDARY DAMAGE MECHANISMS

1. Introduction

We have outlined at some length the three basic primary damage mechanisms to the environment: radiological effects, thermal effects and atmospheric phenomena. The scale considerations in these three cases were complicated enough, but the proper context, at least, seemed to be fairly clear. That is, none of the types of direct damage seem likely--in plausible nuclear wars--to outweigh the disutility of large numbers of casualties and property loss. In none of the three cases did there seem to be very compelling reasons for believing that the damage to the environment would strongly tip the balance against survival and recovery. Putting it another way, the kinds of damage discussed, however expensive they might prove to be in economic terms, would probably not overwhelm man's capacity to respond to the challenge and eventually to recover.

The above question is still open, however, for secondary effects--where it is, in any case, harder to be confident about the answer because some of the chain-reactions which one can envision seem open-ended. That is to say, it is difficult to identify upper bounds for many kinds of things. Who can say *a priori* where an insect plague, or an epidemic, is likely to stop? Some of the intellectual issues involved here were discussed in some detail in the general introduction.

The specific classes of secondary effects which look potentially menacing, singly or in combination, are listed roughly in order of time scale as follows:*

2. Epidemics among humans, animals or crops
3. Pest outbreaks (e.g. insects, rodents)
4. Microclimate
5. Secondary fires
6. Problems of ecological succession
7. Floods, silting, erosion
8. "Balance of Nature"

There are historical examples of most of these kinds of environmental disasters. However, the cogent question is whether, or to what extent, any of them is likely to follow a nuclear attack of realistic dimensions (in terms of present or projected weapons, delivery capabilities, target doctrines, defenses and political-strategic scenarios).

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*The items are numbered in this list according to the corresponding sections in this chapter.

2. Epidemics of Humans, Etc.[1]

Diseases of man (and of animals) are caused by five types of organisms: bacterial (including rickettsial), protozoal, viral, fungal and parasitic worms. The latter are not microorganisms, and their effects are debilitating but seldom acute.* They are long-lived and generally do not complete their life cycles in a single host. Hence they do not multiply to any great extent in the human body and propagation can be controlled easily by "cultural" methods, e.g., inspection of food, sanitation, proper disposal of garbage. Diseases due to worms are deemed unlikely to become a serious menace as a direct consequence of thermonuclear attack.

Fungi are not a serious cause of diseases of animals or man. Less than 50 of the thousands of known species are capable of invading animals or man, and less than a dozen can cause fatal infections. The most common of these is Actinomyces bovis (nevertheless very rare). Only one group, the dermatophytes (which cause skin diseases such as ringworm), can be spread from animal to man or man to man. These infections, while persistent and hard to get rid of, are not usually serious. Under hot, humid shelter conditions fungus diseases of the skin could spread rapidly and become a serious annoyance.

The remaining diseases, bacterial, protozoal and viral, may have epidemic possibilities which could be influenced by conditions following a nuclear attack. To the extent that these diseases are, or may be, acute, they must be considered carefully. Microorganism populations will not, in general, be affected directly by levels of radiation which would leave any survivors among higher plants and animals.** Moreover, any fluctuations arising from differential radiosensitivities would be so rapid, due to the very short reproductive cycle of the organisms, that the effects would be averaged out in the time scale of macroscopic ecological events.

The best guide to probable epidemic threats in a postattack world is past experience extrapolated to take account of likely conditions. Some or all of the following factors may be relevant:

(i) General health. Bodily resistance may be affected by exposure to radiation from fallout. Radiation sickness weakens the disease-fighting capability of the body by destroying the cells which manufacture white blood corpuscles. Other injuries such as burns also reduce resistance to ancillary infection. Inadequate diet may have similar consequences, for example, if vitamin C is in short supply.

(ii) Medical help. Antiseptics, antibiotics, antitoxins and vaccines supplement or increase the natural resistance of the body. Some or all of these might themselves be unavailable or in short supply after an attack, due to destruction of inventories, manufacturing capacity or natural sources, and distribution capability--in conjunction with sharply rising requirements.

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*With some notable exceptions, e.g., trichinosis.

**Critical doses are of the order of 10^6 rads.

(iii) Foci of infection. Although many serious diseases exist at present in North America, generally they have a low incidence in the population. This fortunate fact suggests that epidemics would take some time to become established in a postattack environment--during which period precautionary measures could be taken and social organization, transportation and communication might be partially restored. However, there are two caveats to be considered:

a) Hospitals and first-aid centers would be overloaded with the worst cases of radiation sickness, burns, etc. Hospitals also are endemic sources of some infections (such as Staphylococci) due to the constant presence of sick patients. Food supplies, bed linen, tableware, sanitation gear, etc., are difficult to keep sterile even in normal times. In a postattack environment certain diseases might spread initially within hospitals, eventually infecting outsiders (released patients, employees, visitors) and the general population.

b) Biological warfare might be combined with a nuclear attack. Foci of infectious diseases not normally present may be deliberately introduced by an enemy.*

(iv) Infectiousness. Epidemics, in the familiar sense of the word, are normally caused by organisms capable of very rapid multiplication and spread. Thus, diseases which either develop very slowly or affect a small percentage of those exposed would probably not pose a major epidemic threat. In the latter category might be included TB, syphilis, leprosy, meningitis, poliomyelitis and others.

(v) Mode of transmission. Direct transmission by personal contact or infection via aerosols (droplets in the air) is most conducive to rapid spread. In this category are the common cold and various forms of influenza, scarlatina, smallpox, diphtheria, meningitis, whooping cough, measles, mumps, some forms of pneumonia and cholera. The pneumonic form of plague and anthrax can also spread this way. Transmission via food or water can be very rapid in certain conditions but is comparatively easy to control, at least in peacetime. In this category are most of the enteric diseases such as infectious hepatitis, typhoid fever, paratyphoid and dysentery (both bacillic and amoebic). Such diseases need not be a serious problem, given reasonable precautions. Transmission via insect bites is somewhat less conducive to epidemics and offers opportunities for control both at community level (e.g., large-scale use of insecticides) and by individuals (e.g., mosquito netting, DDT powder, sanitary measures). Many serious diseases are spread by insects, including plague, typhus, tularemia, Rocky Mountain spotted fever, yellow fever, dengue fever, malaria, encephalitis and sometimes anthrax. The main danger here is that diseases held in check by controlling their vectors could spread during a period of postattack chaos. Diseases transmitted by animal bites include rabies and rat-bite fever, among others. Tetanus, anthrax, and various forms of gangrene can be introduced into open wounds. This mode of transmission seems hardly likely to pose an epidemic threat however.

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*This possibility is largely discounted as a rational tactic by most experts, although a minority would argue strongly for giving greater attention to such eventualities.

(vi) Mortality. As a general rule diseases of common occurrence have a low mortality rate. Thus measles, chicken pox, mumps, and influenza no longer seem to pose severe threats. Others such as malaria and amoebic dysentery are more often chronic and debilitating than fatal.

Diseases having postattack epidemic possibilities, judged on the basis of infectiousness, appropriate modes of transmission and high mortality, seem to fall into three categories:

(1) Diseases which might conceivably overwhelm all efforts to control them, given a favorable situation such as a population with low resistance and overstrained medical facilities. The general requirements would be a high rate of infection, direct transmission (easy communicability), little or no immunity, and high mortality. The prime candidates appear to be smallpox, cholera, diphtheria or, conceivably, some virulent new strain of influenza. Fortunately the first two are almost unknown in North America and diphtheria is extremely rare. Anthrax and psittacosis are dark horses as far as natural outbreaks are concerned, but would be very plausible choices for bacteriological attack by a malevolent enemy.

(2) Diseases which might erupt as a result of specific postattack conditions such as breakdowns of sewage disposal systems, chlorination of public water supplies, pasteurization of milk, general sanitary precautions in the food processing industry, etc. Typhoid, paratyphoid, dysentery and infectious hepatitis seem to be the most likely threats. All of these occur occasionally throughout the North American continent. Plague, which is transmitted by fleas from rats to man, is another possibility, although cases among humans in the U.S. are extremely rare. In very crowded quarters, such as fallout shelters, with inadequate facilities for personal hygiene, typhus outbreaks (transmitted by the body louse) are a distinct possibility. Circumstances can also be imagined leading to the re-establishment of reservoirs of malaria, yellow fever, dengue fever and encephalitis in the U.S. These diseases are transmitted by Anopheles, Aedes and Culex mosquitoes, which are widespread in the South.

(3) Diseases of animals and crops raise a number of separate issues which will be discussed separately later.

Past outbreaks and general characteristics of some of the above diseases are summarized briefly in the following.

a. Class (1) Diseases

At the present time there are two strains of the smallpox virus, variola major, which is the classic epidemic variety, and variola minor, which is endemic in the United States and other countries. Variola major appeared in epidemic proportions throughout Europe after the Crusades. It is one of the most contagious of all diseases and is spread by personal contact. During the 18th Century in Europe one person in ten died of smallpox and approximately 96% of the Europeans who survived into adulthood had had the disease. Although variola major is rare in the United States today, as late as 1959, 100 cases were reported in Brazil and over 200,000 cases occurred in India and East Pakistan. Smallpox does not yield to antibiotics, although rehydration and therapeutic measures may help. Vaccination, the standard method of control, often wears off after a few years. Zinsser estimates that 74% of the population would be relatively unprotected if an epidemic should occur. Mortality among unvaccinated children is usually about 80%.[2]

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Smallpox (Variola major)	Pandemic - Europe 1614	Pandemic
	Epidemic - England 1666-1675	Epidemic
	New England 17th Century	Scattered outbreaks
	United States: 1921	89,357 cases with 481 deaths
	1924	45,255 " " 814 "
	1939	9,877 " " 41 "
	1945	345 " " 12 "
	1950	42 " " - "
	Minnesota 1924-1925	1,430 cases; death rate 25/100
(Variola minor)	Minnesota 1913-1923	35,000 cases; death rate 0.3/100

Diphtheria, a bacterial infection caused by Corynebacterium diphtheriae, is spread by contaminated nasal discharges of patients, convalescents or healthy carriers. The disease first appeared in epidemic proportions in France in 1850 and within 25 years had spread to Boston and London. Vaccination and use of the Schick test to identify susceptible individuals in the population has helped in the decline of diphtheria, although in the event of widespread famine following a war it might be as big a problem as it was in parts of Europe during the Second World War. Use of antitoxin as soon as the disease is contracted is helpful; delay in its administration, however, increases the risks of mortality from either diphtheria or one of the possible complications such as myocarditis or bronchopneumonia.

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Diphtheria	1880-1930 Epidemic waves throughout the world occurred every 5-10 years.	Especially after wars and/or famines.
	1920's U.S.	150,000 cases a year with 15,000 deaths.
	1943, 1946 Europe	Outbreaks in countries surrounding Germany (excluding Great Britain) with rise in death rate, i.e., Holland: 1939 0.9/100,000 1946 46/100,000
	1953-1962 U.S.	13,000 cases
	1962 U.S.	432 cases--63% of which were located in the South.

Cholera, caused by the bacteria <u>Vibrio comma</u>, is spread either by contaminated food and water or by direct contact. Use of antibiotics during epidemics does not appreciably lower the mortality rate. Death is often due to dehydration; the most important aspect of caring for persons with cholera is to keep them constantly supplied with liquids, hence the high mortality rate in epidemics where nursing is scanty. The disease is still endemic in parts of India, Pakistan and surrounding regions but is now rare in the West.

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Cholera	Disease first identified in India where it is still serious--1815-1816.	
	1832 New Orleans	5,000
	Baltimore	853
	1849 New York (May 16-Aug.)	5,017
	St. Louis	1,000--10% of population
	Rio Grande Valley	2,000
		Disease persisted in U.S. until 1854.
	1855-56 After the Battle of Alma, France	Cases at the rate of 12,000 per month.
	1883 Pandemic	Worldwide (except in North America)

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Cholera (Cont.)	1892 Hamburg-Altona	17,000 cases and nearly 9,000 deaths in two months. Water was pumped directly from Elbe River into city water mains. The water used by the suburb, Altona, was filtered before it was distributed, and as a result only a few cases of cholera developed.
	1960 (August) West Pakistan	
	1963 (Nov.) East Pakistan & India.	

The influenza virus is noteworthy for its tendency to mutate into virulent new strains to which the population has not previously been exposed. For this reason vaccination is not altogether effective in controlling this disease. Antibiotics can only be used to prevent complications but, as with other viruses, have no effect on the disease itself. Periodic pandemics of influenza began in Asia early in the 18th Century and spread to Europe and the United States. Death during recent epidemics is usually the result of complications such as pneumonia, especially in older patients.

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Influenza	1500 Originated on Malta and rapidly spread throughout Europe.	Worldwide
	1647 Arrived in N. America from Valencia, Spain	
	1918-19 Pandemic	Worldwide: 21,600,000 deaths. Twice as many died from flu as from direct results of war. In U.S. 20% of population infected, with 400,000 deaths during October.

Anthrax is a highly infectious and rapidly fatal disease commonly associated with animals. The causative organism, Bacillus anthracis, is capable of forming spores which may remain virulent in the soil for several years. Pasture infected with spores can remain a source of infection for as long as 20-30 years. The spores may be spread by any contact, direct or indirect, with infected carcasses. Outbreaks of the disease in animals have been traced to contaminated bonemeal in hogfeed (1952, Midwest) and in humans to shaving brushes made with contaminated, unsterilized bristles. In humans the disease may be cutaneous (malignant pustule), pulmonary (woolsorter's disease) or intestinal, depending upon the mode of entry. The intestinal form is always fatal; the pulmonary form is usually fatal; but the cutaneous form may be cured if penicillin or antibiotics are given in the early stages. The mortality rate in herbivorous animals may be as high as 80%. Vaccination and the use of antiserum once animals have been exposed helps to prevent epidemics, although vaccination is not 100% effective. Animals suspected of having died from anthrax have to be cremated or buried under a layer of quicklime so that the spores cannot be picked up by the wind and carried to uncontaminated regions. In the United States there were about 3,500 outbreaks in animals and 483 human cases from 1945-1955.

Psittacosis and ornithosis are so closely related they can be discussed together as a single disease, usually associated with birds, particularly members of the parrot family. The organisms Miyagawanella psittaci and M. ornithosis, usually classed as Rickettsiae or "large" viruses, may be excreted in healthy carriers for several years. They can enter the body on dust particles or aerosols inhaled through the respiratory tract causing an influenza-like disease. Turkeys contract a highly virulent form of the disease which has caused several epidemics among employees in turkey processing plants, e.g. Texas, 1963. The disease may also be spread by person-to-person contact, especially from patient to nurse, e.g. 26 such infections with 13 deaths in Buenos Aires in 1945, and 19 infections with 8 deaths in Louisiana in 1943. There were 563 cases in 1954 and 568 cases in 1956 among humans, but the number has declined since then. Tetracyclines are found to be an effective antibiotic treatment which has reduced the mortality rate from about 20% to 2%.

b. Class (2) Diseases

Epidemics of typhoid, paratyphoid and bacillary dysentery have occurred in the past as the result of contaminated food or water. Epidemics have often been traced to healthy chronic carriers of Salmonella or Shigella bacteria. Public health measures have succeeded in keeping the incidence of these diseases low, but in a postattack environment, such measures may be degraded or interrupted in various parts of the country. Vaccination is possible against the Salmonella but not for the Shigella group. Chloramphenicol is the usual antibiotic treatment for all three diseases.

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Typhoid and Paratyphoid Fevers	U.S. morbidity figures have declined from 2,252 cases in 1953 to 608 cases in 1962 for typhoid fever. Salmonellosis (excluding typhoid fever) morbidity rates, however, have increased from 3,946 cases in 1953 to 9,680 cases in 1959.	
	1897-98 Maidstone, England	An epidemic of an enteric fever occurred in a population of 34,000 with 1,938 cases reported. Attributed to human pollution of the springs which fed the water supply.
	1936 (Aug. & Sept.) Poole & Bournemouth, England	A chronic intermittent typhoid carrier* was visiting in the area. Waste from the house in which he was staying contaminated a stream which was used by dairy cattle. The epidemic of 518 cases scattered over the area was milk-borne.[4]
	1946 Aberystwyth, Wales	Milk-borne paratyphoid epidemic.
	1963 (Spring)-Zermatt, Switzerland	300 cases attributed to a broken sewer line and consequent pollution of drinking water.
	1964 Aberdeen, Scotland	About 400 cases developed within a month as a result of an infected can of corned beef.

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*Epidemics started by chronic typhoid carriers also include 7 epidemics involving over 200 individuals all caused by "Typhoid Mary" who was a cook for 8 different families over a period of ten years. In South Africa 5 localized epidemics since 1941 have been attributed to a native waiter.[3]

Date & Place of Outbreak

Extent of Morbidity & Mortality

Dysentery

Shigella group of bacteria have become primary cause of enteric infection in the U.S. since the decline of typhoid, for example, 38,000 cases in 1944, 16,533 in 1953 and 12,443 in 1959 in the United States.

"During the American Civil War, the annual morbidity rate in the Northern armies was 876 per thousand and the death rate 10.37 per thousand, while in the Southern armies, the situation was equally as bad or worse.

"Dysentery was a major problem in all of the armies during World War I. The British were pinned down at Gallipoli and immobilized in Mesopotamia by dysentery.

"During World War II the English troops in Burma suffered severely from dysentery.

"Montgomery's victory at El Alamein is attributed in part to a large number of dysentery cases among the German and Italian armies."[5]

There are two strains of the hepatitis virus. The infectious hepatitis virus is commonly transmitted through contaminated food or water, while serum hepatitis is usually transmitted during blood transfusions. The disease has been increasingly prevalent in recent years; for example, there were over 50,000 new cases in the United States during 1960. The usual preventive measures are to give exposed individuals gamma globulin before the disease has started and to allow blood plasma to sit six months before being used in transfusions in order to kill the virus. Once the disease has taken hold, the only treatment is rest and diet.

Date & Place of Outbreak

Extent of Morbidity & Mortality

Infectious Hepatitis

A common occurrence during wars. For example, during three months in 1943, 35%-40% of Air Corps personnel stationed in Sicily contacted hepatitis.

Sporadic outbreaks are often the result of contaminated oysters, milk or water, e.g. 1961 outbreak in Mississippi and 1962 in New Jersey.

Serum Hepatitis

Before hospitals began to store blood plasma prior to using it in transfusions, one Chicago hospital reported that over 2% of the patients who received blood transfusions contracted serum hepatitis. The 2% rate is four times greater than 15 years ago despite added precautions.

During World War II, many cases developed after yellow fever vaccinations: 28,585 cases with 62 deaths.

Plague, caused by the bacterium Pasteurella pestis, is a disease which is transmitted from rats to man by way of fleas. "Sylvatic" plague is a form endemic among wild animals in the rural United States, especially in the Southwest, but it rarely spreads to humans. The epidemic version of plague (bubonic or pneumonic) is the classic "black death" that ravaged Europe during the 14th Century. The pneumonic form spreads rapidly by direct contact and is highly lethal. Closely related to plague is tularemia, or rabbit fever, which is endemic in areas with large rodent populations. At the present there are about 2,000-3,000 human cases reported each year. Streptomycin and the tetracyclines appear to be most effective in the treatment of tularemia and both the bubonic and pneumonic forms of plague.

	Date & Place of Outbreak		Extent of Morbidity & Mortality
Plague	14th Century		Cycle known as Black Death--originated in Central Asia and spread to Europe, India, and China. 25,000,000 deaths. Population of Europe reduced by 25% or more, some areas had 80% mortality.
	1664-66	London	70,596 deaths
	1900-04	San Francisco	117 cases
	1907	San Francisco*	179 cases
	1907	Seattle	5 cases
	1914	New Orleans	30 cases
	1919	New Orleans & Oakland	15 cases
	1920	Galveston Beaumont Pensacola	18 cases 14 cases 10 cases
	1924	Los Angeles	41 cases
	(U.S. from 1900-1952: 523 cases of diagnosed plague; 65% fatal)		
	1910-11	Manchuria	60,000 deaths
	1920-21	Manchuria	8,503 deaths

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*Two historical plague epidemics have occurred in juxtaposition with great fires--London, September 1666, and San Francisco, 1907. It is possible that some correlation may be inferred, although there is probably no simple cause/effect relationship.

Murine typhus, a Rickettsial disease, is endemic in rodent populations in the United States and is transmitted by fleas. The historic scourge, however, is louse-borne typhus, which has a high (up to 70%) mortality. Drugs do not help much against the Rickettsiae. The best control yet developed is delousing by means of 10% DDT powder (if available) and vaccination. Strains of lice resistant to DDT appeared during the Korean war, but U.S. troops were protected somewhat by vaccination. In an epidemic among unvaccinated British troops there was a 32% mortality rate. Rocky Mountain spotted fever, spread by ticks, is a very similar disease which is widespread in the western United States.

	Date & Place of Outbreak		Extent of Morbidity & Mortality
Typhus	1528-30	Naples	20,000 deaths
	1812	Moscow (Napoleon's Army)	300,000 deaths. Over 56% of the soldiers in the army died of typhus during the retreat.
	1846-47	Ireland/Canada	75,540 Irish immigrated to Canada 30,265 sick with typhus: 1) 5,293 died at sea 2) 8,012 died at Quebec 3) 7,000 died at Montreal
	1914	Serbia*	in less than 6 months 150,000 died
	1917-23	European Russia	30,000,000 cases and 3,000,000 deaths
	Korean War		outbreaks among all troops
	1959 (Spring)	Ethiopia	500 deaths
	1959 (Summer)	Mexico	74 deaths

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*Typhus has often accompanied evacuations or military operations due to the unwashed and unsanitary conditions which tend to accompany these movements. Zinsser[6] makes an excellent case for his contention that typhus has affected the outcome of a number of critical military campaigns in history, e.g. Napoleon's disastrous retreat from Moscow in 1812, and the Austrian invasion of Serbia in 1914.

Malaria is caused by several species of the Plasmodium protozoan and is carried by mosquitoes of the genus Anopheles, several species of which occur in the United States. The disease was formerly endemic but has been pushed south by swamp drainage, public health, and other control measures. It could return if, for example, insecticides became scarce and conditions chaotic. The yellow fever virus is usually thought of as a tropical disease, as is malaria, but its principal vector, the Aedes aegypti mosquito, is common in the Southern states. The same mosquito also carries the virus of dengue (breakbone) fever. Culex spp. mosquitoes are responsible for the transmission of endemic St. Louis encephalitis virus, another serious disease. Any of these diseases could flare up given a focus of infection and a relaxation of mosquito controls. Preventive drugs are available for both malaria and yellow fever but not for encephalitis. As is the usual case with viruses, there are no specific chemotherapeutic or antibiotic treatments available for either yellow fever or encephalitis.

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Malaria	1935 U.S.	900,000 cases with 4,000 deaths
	1934-35 Ceylon	66,000 deaths
	1942 Egypt	125,000 deaths
	1952 (July) California	A returned Korean war veteran with malaria suffered a relapse while camping in the California Mountains. Mosquitoes, which bit him during the relapse, transmitted malaria to 9 other persons, who suffered attacks that fall. The next spring, 25 more people came down with the disease in various parts of the state. All cases were traceable to the original patient.[7]

Since 1953 approximately 3,500 cases of malaria reported in U.S.

In the world, approximately 200,000,000 clinical cases and 2,500,000 deaths each year, are a result of the disease transmitted by the bite of 85 or more species of the Anopheles. The disease is distributed in the broad belt around the globe in the tropics and subtropics.

	Date & Place of Outbreak	Extent of Morbidity & Mortality
	1958 Ethiopia	3,000,000 cases 100,000 deaths

	Date & Place of Outbreak	Extent of Morbidity & Mortality
Yellow Fever	1802-04 Haiti (Santo Domingo)	22,000 out of the 25,000 French soldiers in Haiti died of the fever (resulting in the establishment of the first Republic of Haiti under Toussaint L'Ouverture and eventually the sale of the Louisiana territory by Napoleon to the U.S.).
	1880's Panama	Yellow Fever also contributed to the failure of the French Panama Canal Company under F. de Lesseps. A prerequisite of ultimate American success in this venture was eradication of the *Aedes aegypti* mosquito from the Canal Zone.
	1928-29 Rio de Janeiro	59% mortality
	1937 Philadelphia, New Orleans Memphis, New York City	
Dengue Fever	1922-23 Southern states (centralized in Texas & Louisiana)	over 1,000,000 cases reported
	1927-28 Greece	over 1,000,000 cases reported
	1936 Florida	
	World War II Japan	over 1,000,000 cases reported
	1963 Puerto Rico	17,838 cases reported by mid-November after epidemic began in the summer.
	Jamaica	978 cases reported

	Date & Place of Outbreak	Extent of Morbidity & Mortality
St. Louis encephalitis	1933 St. Louis	1,000 cases. In 1932 during the summer many cases of encephalitis occurred in Cincinnati, Ohio and Paris, Illinois. Unusually dry summer led to stagnation of polluted streams, etc., which in turn provided increased breeding ground for *Culex* mosquito.
	1937 St. Louis	
	1938 Massachusetts	34 cases with 25 fatalities. An epidemic of encephalomylitis is also occurred at this time among horses.
	1941 Minnesota, North Dakota and Canada	3,000 cases
	1947 Louisiana	Epidemic occurred among horses and pheasants, but not humans.
	1952 San Joaquin Valley, California	Unusual snowfall, floods and wasteful irrigation practices (mosquito breeding spots).
	1954 Hidalgo County, Texas	600 cases
	1956 Massachusetts	13 cases with 10 fatalities.
	1962 Florida	An epidemic that started in July consisted of 180 cases in 5 weeks. By September 14 there were a total of 223 cases with 18 fatalities.

c. Class (3) Diseases: Animals[8]

There are only four groups of animals of substantial economic importance in the United States; namely, cattle, swine, sheep, and poultry. All are sources of food and/or fiber. Horses and mules have been largely replaced by motorized vehicles. Cats and dogs are primarily kept as pets, only a tiny percentage serving any other function.

Wild animals and fish interact with man in a more indirect way. The ecological relationships involved are more complex and probably an order of magnitude less critical than are farm problems arising as a result of nuclear attack. Hence we shall not discuss them.

With regard to domestic animals, disease treatment and prevention methods are generally similar to methods used for humans, e.g. clean food and water, insect control, improved diet, etc. There are three major differences:

(1) Contacts between animals and man or other animals can be deliberately controlled, as can diet and other aspects of life (including reproduction).

(2) Diseases, once recognized, can be "treated" by simple isolation and destruction of sick animals. This was done and is being done for a number of diseases, e.g. hoof-and-mouth disease, bovine TB, pleuropneumonia (of cattle), dourine and glanders (of horses), hog cholera, rabies, brucellosis, and others.

(3) Animals are unable to summon medical aid at the first onset of the disease, but must wait until symptoms are obvious to an (often untrained) observer.

Items (1) and (2) clearly operate in favor of effective disease control. Item (3) is moot, since experienced, alert farmers are probably at least as good at diagnosing trouble among their animals as untrained civilians are at recognizing illness in themselves. Diseases may be transmitted through a whole herd or barnyard (in a bad outbreak) as a result of direct contacts between animals, but transmission from herd to herd or farm to farm is inhibited by the relative isolation of the various groups of animals from one another. This does not totally inhibit diseases borne by wind or mobile insects, however.

A thermonuclear attack might influence the spread of diseases among animals indirectly by causing lowered disease resistance, by inhibiting treatment and control, and by affecting the several mechanisms of propagation. As with humans, general health of animals will be affected by radiation, mainly external. The long-term hazards due to internal doses of radiation are probably unimportant from the medical point of view. Supplies of medicines, antitoxins, vaccines, etc., would probably be limited, and surviving inventories and capacity would also be subject to increased demand from humans. This problem might be rather acute in some circumstances.

Disposal of carcasses of diseased or radiation-killed animals could be a problem of the first magnitude. To the extent that it is found to be impossible (e.g. due to residual radioactivity) to bury or burn all of them immediately, breeding grounds for many disease organisms and insects (particularly flies) would be available. Very large populations of some pests could be built up. The consequences seem more likely to be in the nature of a general health hazard, however, rather than a danger of breeding specific epidemic diseases, since the organisms causing disease in animals generally perish with the host. This should be studied in more detail, however. For example, the spore-forming bacteria Bacillus anthracis, producing anthrax (one of the most widespread and dangerous diseases both of animals and man), retain their viability for many years in soil, water, or elsewhere, even under extreme conditions of temperature and humidity, although they do not multiply rapidly anywhere except in the blood stream of a warm-blooded animal.

As in the case of humans, diseases posing postattack epidemic threats would probably have to be (1) highly infectious, rapidly developing and characterized by high mortality, and (2) spread by direct contact between animals, inhalation of dust or aerosols (e.g. droplets from nasal discharges, etc.), or ingestion via pasture contaminated with urine or feces.

Diseases which require innoculation directly into the blood stream do not normally result in epidemics, since wounds or abrasions are a condition of entry. However, if the screwworm fly should again become widespread north of the Rio Grande--perhaps as a result of postattack chaos and the interruption or suspension of control programs--conditions favoring this type of spread might be established.

Diseases spread by insect bites could become uncontrollable and epidemic if a large enough reservoir of cases were permitted to develop unrecognized or without countermeasures. However, this threat seems more potential than actual, since the same potential threat exists in normal times and scarcely ever materializes.

Descriptions of a few diseases with epidemic possibilities follow.

Hog cholera, also called swine fever, is a viral infection which is spread by contaminated food or water or through abrasions in the skin. The virus moves through the body in the blood and is present in all body secretions, thereby providing new sources of infection. Occasionally recently vaccinated hogs are capable of transmitting the disease. The virus may be carried to other areas on any infected material such as food or feces which is transported out of the contaminated yard. The mortality rate is very high. Animals that recover are usually chronic cases depending upon the virulence of the virus and the resistance of the hog. There is a vaccine for preventive purposes but no known treatment. Because there is a delay of about five or six days between exposure and the first visible symptoms, during which time other animals can contract the virus, the disease is often more advanced in the herd than it appears to be.

Leptospirosis is a disease caused by several species of the Leptospira bacteria and in cattle produces effects ranging from milk loss and abortion to death, with a mortality rate of 7-45%. Various rodents such as rats and voles act as reservoirs of the bacteria. Foci exist in California, the Midwest and the Gulf Coast. Man and other animals are also susceptible. Carriers may excrete the bacteria in urine for several months. Animals usually contract the disease by ingesting contaminated food and water or by entry through abrasions in the skin. The infection is spread most rapidly in large, close-living herds in damp regions. Streams may carry the bacteria for many miles into uncontaminated regions. Antibiotic treatment is effective if given early enough, and vaccination is available for cattle and dogs for certain species of the bacteria.

Foot-and-mouth disease, a highly contagious viral infection which spreads rapidly through the skin or intestinal lining into the blood stream, effects almost all cloven-footed animals. The disease has not occurred in the United States since 1929; however, outbreaks of the disease occurred in Mexico from 1946-1952 and in Canada in 1952. Control measures involve slaughtering diseased animals and prohibition of imports of hay, straw or meat from countries not free of the disease. The virus is excreted in saliva, feces, urine and milk and can be transmitted mechanically by any article that comes in contact with the infected animal. A vaccine is available for preventive purposes but has only a six-month effective period. Although the mortality rate is only about 5% in adults, it is higher in calves and may approach 50% in severe epidemics.

Rinderpest is a highly contagious viral disease of cattle which proceeds rapidly and has a mortality rate of 15-75%. The mortality rate tends to be higher in areas in which the disease is not endemic, as in the United States. The virus is discharged in all body secretions and enters via ingestion of contaminated pasture or forage.

Pullorum, a bacterial infection of chickens and other birds caused by Salmonella pullorum, is a highly infectious disease which can be transmitted through the egg to a new chick or may spread by way of dust particles or contaminated food or water into either the respiratory or digestive system. In young chicks the mortality rate may be as high as 80-90%, but the death rate decreases with age. Chicks who recover usually remain lifetime carriers and sources of infection for new chicks. Control of the disease requires breaking the egg transmission cycle by testing adult chickens and destroying infected ones in order to make sure that only healthy chickens lay eggs.

Newcastle disease is a highly infectious virus disease of poultry which has an average mortality rate of 30-40% but may run as high as 100%. The virus is excreted in the saliva, nasal secretions and droppings of infected birds as well as healthy carriers--occasionally for as long as two or three months. A vaccine is available against Newcastle disease and infectious bronchitis, another viral disease of chickens which spreads by direct or indirect contact throughout poultry houses. Another highly lethal viral disease of poultry is fowl plague, for which there is neither vaccine nor treatment at the present.

d. Class (3) Diseases: Crops[9]

One type of stress with which organized agriculture must cope is plant diseases caused by pathogenic organisms including viruses, bacteria, fungi and nematodes. Natural constraints on the spread of disease are of several sorts:

(1) The virulence of the organism

(2) Factors affecting resistance to infection

(3) Factors affecting modes of pathogen transmission

In regard to point (1), the most salient question is whether the lingering effects of nuclear attack, principally radiation from fallout, are likely to cause an increase in the rate of mutation (or natural evolution) of pathogens. The extent to which this "mutation" factor is important depends on how much reliance is placed on cross-breeding to obtain immunity to disease. In the case of plants, particularly cereal grains, the development of hybrid varieties of plants is sometimes said to be in a neck-and-neck race with the natural evolution of dangerous new strains of blights, rusts or viruses. It has been argued that thermonuclear war could conceivably upset this equilibrium by increasing the rate of mutation while inhibiting the production of new hybrid species. However, this is mere conjecture at present, since the exact role of ionizing radiation in producing mutations, or of mutations in evolution has not been established. Indeed, recent evidence suggests that likely levels of radiation are likely to be ineffective at inducing mutations or increasing virulence.

Resistance to infection might be sensibly lowered by heavy but nonlethal doses of radiation. This has not been directly demonstrated but it is certainly plausible. The rate of insect defoliation has actually been observed to increase by as much as an order of magnitude on radiation-weakened trees. That resistance to attacks by microorganisms should drop correspondingly is an easy conjecture. On the other hand, there is some data which might be interpreted as evidence that at low levels of exposure resistance to disease may actually increase.* If this were shown to be a general phenomenon, crops at the outer fringe of a fallout zone might actually turn out to be unusually healthy--an important point, in view of the fact

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*Results consistent with this hypothesis are treated with great caution and skepticism by scientists, both because one simple theory predicts that somatic and genetic damage should linearly increase with dose, and because nobody wants to be accused of trying to prove that "radiation is good for you."

that for most attacks far more land area is likely to be in the 25-100 R zone than within the 3000 R isodose contour.

Pathogen transmission is a subject with complex ramifications. Various agencies are responsible. Fungus spores and certain bacteria are often transmitted by wind. Some organisms remain in the soil from one year to the next (providing one of the incentives for crop rotation). Other organisms are transmitted via infected seed. Still others are carried by man, animals, birds or insects. Insects, in particular, are so closely involved with the transmission of plant diseases that specialized synergistic relationships have often evolved.

The simplest case is where the insects merely serve as a vehicle. The insect picks up spores or pollen (on its feet or body) from a sick plant and deposits them on a healthy one, more or less at random. Honeybees and other nectar-collectors are often involved this way (e.g. in spreading fire blight of apples and pears).

Sometimes the insect is specifically attracted to the diseased plant by characteristic odor, but otherwise the interaction is essentially mechanical. Thus flies are attracted by a sugary substance produced by ergot (fungal) disease of rye. Bark beetles are thought to be attracted to weakened or diseased trees by the smell of fermentation from the cambium layer. In some instances wind-blown spores must find openings, such as insect bites, to grow on the new host. More often insects are required simultaneously for both functions, transportation and penetration of the outer skin of the plant. Many fungal diseases of trees gain entrance with bark beetles; for example, the Dutch elm disease and the blue stain disease of pine trees spread this way.

A still more intimate relationship exists, in some instances, where the insect serves as an alternate host (e.g. for overwintering: bacteria Bacterium stewartii, which causes wilt of sweet corn, winter in the bodies of the corn flea beetle). The relation may be parasitic or even symbiotic if, for example, the bacteria supply vitamins or enzymes for the insect host.

Some fungal diseases involve mating between spores of opposite sexes. One case is the black stem rust of wheat, Puccinia graminis, which winters on barberry leaves where a sexual mating must take place. This is normally accomplished with the help of insects feeding on the leaves.

One mechanism whereby the aftermath of a nuclear attack might influence the spread of diseases (or insect pests themselves) has been suggested by Stonier.[10] A number of diseases and pests move from south to north as the growing season progresses. The stem rusts of wheat, mentioned above, are one example in which wind is the primary carrier. Other diseases are carried by insects which winter in the south and gradually move north as the year advances. Fallout patterns following a nuclear attack would tend to run east-west, especially across the Mississippi Valley and the Great Plains. The northerly progress of insects and wind-blown spores would therefore be interrupted at intervals by swathes of fallout-contaminated land. The consequences might depend on the time of year.

An attack before the crops had been planted would deposit fallout over fallow or ploughed fields. Farmers in contaminated areas would probably not attempt to plant. Hence the fields would produce mostly weeds and grass from stray wind-blown seeds (or nothing at all, if the fallout were heavy), which might not be suitable hosts for pests of crops and would act as "attenuators" of the northbound vectors.

An attack after planting would find partly grown crops, which would presumably be weakened by radiation from fallout. Lack of attention by farmers would subsequently result in further loss of over-all ability to resist infection. The result might well be the reverse of the previous example, e.g., the radioactive strips of weakened crops might "amplify" the disease vectors, paving the way for a disastrous outbreak.

e. Overview

Nuclear attack would probably not cause epidemics, but would remove some of the constraints which ordinarily inhibit them. That the incidence of disease would rise in a postattack environment is hardly in dispute. The question is: how much?

Conditions which permitted the devastating plague and typhus epidemics of the Middle Ages would hardly recur today, regardless of the extent of physical destruction caused by war, barring totally unforeseen circumstances. The difference between 15th and 20th century is striking: once men attributed disease to evil spirits, surplus blood, or miasmic airs. Today the role of rats, fleas, flies, mosquitoes, lice, polluted drinking water, etc., are very widely known, while sewage treatment, sterilization, chlorination, and antisepsis, are equally widely practiced by the public. Not only is the level of sophistication of the lay public much higher than in previous centuries, but there exists an effective medical and public health profession and a number of institutions and agencies charged with preventing outbreaks, diagnosing them early and taking active countermeasures. In the circumstances, epidemics of the classical type seem very unlikely, even if the efficiency of the agencies responsible for health matters are considerably reduced.

The possibility of some sort of pulmonary infection spread through the air--similar to the 1918 influenza pandemic--and therefore not controllable by normal means (except isolation) cannot be ruled out, but neither is it easy to see how such a hypothetical disease would be brought about by plausible postattack conditions.

A substantial temporary rise in the death rate from diseases of all sorts (perhaps by a factor of 3 or 5 but not 100), is the most likely concomitant of nuclear attack. The casualties seem likely to be small in comparison with casualties from radiation, blast or fire.

3. Pest Outbreaks

There are three classes of universally recognized pests (apart from disease organisms), insects, rodents and rabbits, and "weeds." In various local situations the word "pest" might have other connotations, e.g. some kinds of birds, giant snails, marauding raccoons, etc. In the United States (circa 1965) it is probably reasonable to concentrate mainly on the three major groups, although some of our remarks will have more general applicability.

The fundamental question is whether the aftermath of a nuclear attack is likely to produce conditions favoring such outbreaks. To treat it, we must try to understand, at least in general terms, the population dynamics of the major pest species.

Demographers and economists since Malthus have argued the notion that human population is constrained basically by food supply. This idea has become so axiomatic that many people tend to assume, without critical examination, that other animal populations are controlled in the same way. Even a simplistic critical examination reveals that the truth is not quite so simple. A slightly more sophisticated approach is to recast the problem in terms of death rate (e.g. resulting from predation or starvation) vs. birth rate (e.g. fertility, breeding conditions). For example, it might be argued that if insects as a class find food easier to obtain, their numbers may increase and vice versa. Or, one might argue, if the vertebrate predators of insects (birds, mammals, lizards, etc.) are depleted in numbers, then insects may prosper and, again, vice versa. Both propositions may seem to be unnecessarily qualified, but neither is actually so. The causal relation implied in the two statements would be invalid in any situation where productivity of the ecosystem (in terms of protoplasm or biomass) is limited by some factor other than food or predation. Water, sunlight, temperature, humidity, mineral elements, shelter, favorable places to build nests or lay eggs, may be limiting in various circumstances. Increasing the supply of any element which is not being fully utilized already will not lead to a radical change in the basic interrelationships.*

In a number of biomes specific limiting factors are fairly easy to identify (see Table 4-1), but in other cases a rather deep analysis would be needed.

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*A more careful argument would have to take into account the fact that these limiting factors are not all independent of each other. For example, a very healthy organism can survive greater extremes of temperature than a sickly one, etc. There is no sharp cutoff in most cases, such that the system suddenly fails to operate beyond a well-defined point. Rather, an ecosystem can be thought of as having certain income (production of protoplasm) which can be spent either in consumption (maintenance) or in investment (new growth). Each necessary element (water, light, etc.) has an associated "cost" which is low as long as utilization is small compared to the amount available, but rises sharply as utilization approaches 100% of total supply. Growth ceases when total production is required for maintenance.

Table 4-1

Limiting Factors For Selected Biomes and Populations

Ocean, upper layers	phosphorus
Ocean, lower layers	sunlight
Rivers, polluted	oxygen--dissolved
Forest, floor and lower story	sunlight (and water)
Forest, upper story (dominants)	density
Birds in farm country	nesting sites
Birds in Forests	density
Carnivores, Insectivores	food
Graminivores*	predation/food
Fish	predation/food/oxygen
Fungi	temperature and humidity
Agriculture	usually one of: water/ nitrogen/phosphorus/calcium/ length of growing season/ soil porosity and humus content.
Desert vegetation	water

One of the most important animal communities from our point of view is, of course, arthropoda (which includes insects). We are particularly concerned with the question of whether and, if so, to what extent, insect populations are food-limited or predator-limited.

As regards the first suggestion, one can assert with considerable confidence that insect populations are not, as a rule, food-limited. This is a corollary of the fact that seldom, if ever, do insects consume more than a small fraction of the available food. The occasional plagues of locusts and/or grasshoppers in semi-arid lands are exceptions warranting special consideration, but there are almost no other examples on record. One reason complete devastation is so unlikely is that most plant-eating insects are specialists living off one or a few species and scorning the rest. Grasshoppers are one of the very few types of insects which will eat practically anything green. Among the familiar pests, the only others with really broad tastes are the Japanese beetle, the gypsy moth and the codling moth (the latter two being pests of deciduous trees).

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*Grass-eaters.

There is more evidence in favor of insects being predation-limited, at least on occasion. Birds have sometimes been credited with spectacular interventions to control local epidemics of insects. A statue in Salt Lake City was erected in honor of seagulls which allegedly suppressed, just in time, a disastrous 19th Century outbreak of Mormon crickets. Other cases have been cited along the same lines, but not with sufficiently high frequency to suggest more than that a local concentration of birds may sometimes decimate an unusually large local population of insects.* There are many more instances where large populations of insects proceeded along their destructive way without serious interference. For example the Engelmann spruce bark beetle epidemic in Colorado (1940-1950) was substantially unaffected by the efforts of woodpeckers which, in effect, merely nibbled at the edges. One possible reason for this is that the woodpecker population density could not increase enough--being otherwise limited--to make inroads on the overwhelming numbers of insects.

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*A quick survey of the literature turned up the following instances:

-- Blackbirds have been responsible for notable triumphs against caterpillars (California orchard near Hayward, 1901), Cankerworms (california orchards near San Jose and Sonoma County, 1908) wireworms (irrigated fields near Turlock and Modesto, California, 1919), fall army worm (peanut fields in Florida, 1919), cotton bollworm (southern plantation, 1919), alfalfa weevil (Utah, 1920), yellow-striped army worm (asparagus field in California, 1925; vineyard in Eldorado County, 1929), and grasshoppers (berry patch in California, 1937).[11]

-- Birds of various species cleared a 320-acre tract on Salt Creek near Lincoln, Nebraska of locusts during the outbreak of 1875. Again in 1877, in one spot on Salt Creek 135 locusts per square foot were counted, but birds flocked to the area and dispatched them all within a month.[12]

-- Western meadowlarks suppressed an outbreak of Mormon crickets near Adrian, Washington in the fall of 1918.[13]

-- English sparrows were credited with controlling the alfalfa weevil in Salt Lake Valley, 1910-1911.[14]

-- Woodpeckers flocked to an infestation of Engelmann spruce bark beetles in Kootenai National Forest, Idaho, in the winter of 1937-1938, apparently destroying 75-80% of all the overwintering broods above the snow line.[15] Again, woodpeckers did good work in an Engelmann spruce bark beetle outbreak in the White River National Forest, during the summer of 1947. This time the mortality of the brood approached 100% in some places.[16]

-- English sparrows (Massachusetts) and hairy woodpeckers (Ohio) are credited with exterminating tussock moth outbreaks by disposing of virtually all egg-masses laid above the snow line (90%).[17]

-- Starlings controlled infestations of brown-tailed moth and gypsy moth in Massachusetts by consuming 60% of the larvae.[18]

It is undoubtedly true that the total numbers of certain types of insects are held in check by bird predation in areas where nesting sites are plentiful. Even though all the sites may be occupied, the number of eggs laid, the number hatched and the number fledged depend strongly on the availability of food. Thus the more insects there are, the greater the pressure of predation. The following season, however, the number of nesting pairs can be no greater than the maximum afforded by the area, so that the increased bird predation does not carry over except to the extent that there may be some extra bachelors or spinsters around. (Being weakest and least aggressive, these tend to die off quickly.)

Although there is no certainty that insectivorous birds play a critical part in controlling agricultural insect pests, they undoubtedly do consume vast numbers of insects. It is known that insects comprise two thirds of the yearly diet of the common land birds in North America. The insect food preferred by each species of bird depends on the season and the range. For example, robins are known to eat insect larvae in the early spring and caterpillars, grasshoppers, bugs, spiders and various beetles during the rest of the year. Most other common insect-eating birds show the same fairly cosmopolitan tastes in their diets, with a few exceptions. As a rule, swallows, flycatchers and swifts catch insects in the air; whereas, members of the thrush family (robins, bluebirds and thrushes) and blackbirds consume ground-living insects. Woodpeckers generally pick insects out of the bark of trees. Flickers, although members of the woodpecker family, seem to prefer insects, especially ants, found on the surface of the ground. Chickadees, crows, starlings, jays and others live partly on insects and partly on seeds and fruit. Except for woodpeckers, most insect-eating birds must migrate, due to inadequate winter food supply in the higher latitudes.

As an indication of the quantities involved, Stonier[19] quotes a study of English sparrows in Salt Lake Valley which suggested that one brood of birds, during the 10-day period before leaving the nests, would consume approximately 20,000 insects (alfalfa weevil larvae or others of equivalent bulk).

There may also be some predation-limiting in the case of skunks, bats, shrews, moles and other mammalian insectivores, which are themselves food- or shelter-limited. Shrews, for example, normally consume their body weight in insects and eggs every three hours or so. Shrew population is probably limited by the availability of winter shelters affording sufficient food. Faced with starvation, shrews will attack and eat mice or other animals larger than themselves. Bats are probably shelter-limited, requiring protected cases or holes to sleep in by day and for hibernating in winter. A certain minimum density of insect life is required to support a single mammal, but the number of surviving young per litter and the number of litters in a summer season will increase sharply if greater food supply warrants it. Skunks and bats are larger and, despite lower metabolic rates, require larger absolute quantities of insect food. To survive the foodless winters, they must hibernate. Mammalian predation can increase very rapidly to take advantage of increased food supplies. Unfortunately, mammals are limited largely to ground-level or underground supplies (or nocturnal flying insects in the case of bats) and cannot easily control the leaf-chewing insects which normally do greatest damage.

It is clear, however, that "predation-limiting" is a misnomer. Preation is only limiting in the indirect sense that progressive income tax is limiting. As with income tax, predation may increase on a rising scale, but it probably seldom takes more than 100% of an incremental increase in insect population, as the notion of "limiting" implies. Actually other factors eventually put the lid on (both on income and on insect population).

For insects the relevant constraints include food predation, parasitism, disease, temperature, humidity, physical surroundings and human intervention. Table 4-2 lists 18 of the most destructive insect pests, together with various constraints on their populations, which have been identified by a search of the available literature. It is probably reasonable to assume that the pattern which seems to emerge is typical of other insect pests as well.

A nuclear war would presumably affect insect pest populations in two ways:

(1) by direct radiation damage, either external or internal--mainly through sterilization due to β-radiation;

(2) by altering critical constraints on populations. Unfortunately (from the point of view of the analyst) these constraints are exceedingly complex and variable, as Table 4-2 shows.

The first mode of interaction has been discussed in the chapter on radiological effects. Due to rapid β-decay, weathering, and rapid turnover of insect populations, the direct damage would probably be largely restricted to a single season. The residual consequences would be selective temporary reductions of certain species populations generally lasting only a year or two.

Ecological controls--predation, parasitism, disease, food supply--involving other organisms with very short life-cycles would presumably also return to preattack homeostatic equilibrium within a season or two.

The temperature-humidity factors are likely to change only if nuclear weapons effects are capable of strongly influencing the weather. The various mechanisms which might plausibly be involved were discussed earlier (Chapter III). However, it should be noted that any change in weather conditions is likely to favor some insects and hurt others, so that the net balance of effects is hard to determine. Moreover, extremes of weather occur each year as a matter of course in one location or another without major effects on insect life (with the possible exception of grasshoppers, discussed separately later on). Forest pests such as the bark beetle, *Dendroctonus engelmanni*, the villain of the 1940-1950 outbreak in Colorado, are also likely to profit by the creation of favorable breeding opportunities as in areas of fire or radiation weakened trees--to the extent that availability of preferred food supplies is otherwise limiting. A quantitative prediction of the extent of the likely damage due to this kind of synergistic interaction is one of the most difficult, yet fascinating, questions which arises. Some of the considerations relevant to building appropriate mathematical models to handle the analysis are discussed in more detail in Appendix D. The crucial point here is that trees are very long-lived, hence an imbalance of the

Table 4-2

Insect Constraints

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Boll Weevil (*Anthonomus grandis*)	Cotton bolls	About 50 insects attack boll weevil and may destroy 16% of larvae.	May act as alternate host to parasites of other weevils.		Rain favors weevil increase by increasing plant growth & decreasing enemies. Adults able to float during floods or heavy rains.[20]	About 95% of the hibernating adults die. Many of the rest die before cotton plant produces squares in which eggs are laid.		Burning or deep plowing under after harvest. Plant certain plants such as blackberries, cowpeas or hedges which have pests whose parasites also attack boll weevil.[21]
Pink Bollworm (*Pectinophora gossypiella*)	Cotton plant blossoms, bolls and seeds.				Resting stage primarily due to extremely dry weather in summer or early fall. If followed by a lot of rain, larvae develop into pupae, then into moths. But by that time cotton stalks have been destroyed after harvest.	Larvae may enter resting stage, diapause, when weather becomes cool or dry or when food supply decreases. May remain in this stage for 2-1/2 years.		Cultural practices. Chemical spray or dusting.

Table 4-2

Insect Constraints (Cont.)

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Bollworm also called Corn Earworm (Heliothis zea)	Cotton bolls. Corn: silk, kernels at tip.	Orius insidiosus and several species of Coccinellidae and Chrysopidae. Corn earworms become cannibalistic under extreme competition.[22]		Bacterial disease introduced into insect via nematode.	Eggs destroyed by mechanical force of rain during storms. Larvae submerged via rain--early spring. After 17 hrs. most survive, but larger larvae cannot survive. "Pupae could not withstand twenty-four hours submergence in rain at normal summer temperatures, but at a temperaature of from 50° to 60° F. they were unharmed by from four to six days' submergence."[23]	Overwinter in pupal stage, but cannot survive winter north of 40° north latitude.[24]	Third generation attacks cotton. (First two develop on corn, tobacco & other plants.)	Introduction of nematode carrying bacterial disease. This method found to cause up to 60-70% insect pop. reduction, but some people do not think that is an adequate figure for biological control purposes[25]
Tobacco Budworm (Heliothis virescens) Often mistaken for H. zea.	Buds of tobacco plant as well as cotton.							Biological control as mentioned above.
Fir Engraver Beetle (Scolytus ventralis)	(All stages of life cycle passed beneath bark.)	Predators and parasites may destroy as much as 84% of brood. All predators and parasites found to increase along with any increase in beetle population. Ostomatid beetle, Temnochila virescens Clerid beetle, Enoclerus lecontei (Among others)					Beetles attracted by smell of fermenting phloem. Causes of outbreaks seem to be lowered resistance of trees, possibly due to infestations by other insects &/or drought.	Chemicals. Destruction of heavily infested trees.

Table 4-2

Insect Constraints (Cont.)

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Engelmann Spruce Bark Beetle (*Dendroctonus engelmanni* Hopk)		Potential survival from cold temp. extremes of beetle *predators* found to be higher than that of host, although mortality rate remains in proportion with beetle mortality rate.[26] Woodpeckers are fairly effective controls if densities are not too high.				Beetle quite susceptible to effects of low winter temp. especially when very cold weather is preceded by moderate temperature. 1953-4: moderate Dec. & first half Jan. End of Jan. very cold--as low as -70° at Rogers Pass, Mont. Mortality lower in areas where insects had been protected by snow. Avg. mortality 42%. Mortality range followed sub-zero temp. ranges.[27]		
Bark Beetles in general	Fermenting trees.	Mites eat eggs & larvae to great extent. Very important in control of beetles.[28] Birds, especially woodpeckers	Nematodes		Excessive rainfall during flight of adults reduces progeny and activities. Those making burrows (in addition to the eggs & larvae) may be drowned in tree sap which is more abundant when soil moisture is high.[29]	Extremely low winter temp. kill some bark beetles. Ore. temp. of -50° F. destroyed 80% of beetles. But within 2 yrs. pop. back to normal.	Most susceptible trees: slow growing ones, crowded, older, lacking in vigor.	Trap logs. Chemical spray Selective logging of sick trees.

Table 4-2

Insect Constraints (Cont.)

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Conditions	Intervention
Spruce Budworm (*Choristoneura fumiferana*)	Foliage of balsam fir.	Birds thought to be main control in 1947.	During outbreaks in Ont. and Quebec, parasites increased: 62% in 1946 72% in 1947 75% in 1948. (30)	Insignificant. In the West in one area where parasitization was low, disease killed 60% of pupae, but this was the only area with high disease mortality.	Greenbank associated spruce budworm outbreaks with a period of dry & sunny summers during 4-5 consecutive yrs. before outbreak. (During dry yrs. male strobili were more abundant--led to higher larval development.[32] Wellington saw "correspondence between spruce budworm outbreaks and periods of decreasing or minimal cyclonic storms."[33]		Fast-growing trees more resistant than older ones. In 1947, composition of Adirondack forest favored enemies of spruce budworm. (Hardwood mixed with spruce-fir stands.)	Maximum control possible when larvae are in 4th or 5th instars. Chemicals.
		Over-all mortality 73%.[31]						
Mormon Cricket (*Anabrus simplex*)		*Chlorion laeviventris*. Crows, hawks, meadowlarks & misc. small birds.	Egg parasite: *Sparasion pilosum*.		Abnormally cold & wet weather for almost a month has caused pop. decline or has at least weakened pop. & lowered reproductive capacity.[34]		Migrate when air temp. is 65-95° F. and wind velocity less than 25 mph.	Galvanized iron barriers. Petroleum distillate placed on irrigation water. Chemicals.

NOTE: Most important constraint seems to be weather--climatic decline causes population outbreak which eventually leads to mass starvation. Population not reduced until starvation and meteorological conditions come into play.

Table 4-2

Insect Constraints (Cont.)

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Chinch Bug (*Blissus leucopterous*)			*Eumicrosoma benefica*: parasite of eggs.	Packard & Benton think that fungus disease, *Beauveria bassiana* is probably the most destructive enemy.[35] Old chinch bugs particularly susceptible to fungus. Fungus spores found wherever host is present. May be exterminated by fungus *Sporotrichum*, but fungus will not grow if humidity is less than 90%.[36]	Heavy rain when chinch bugs are about to hatch may cut down their destruction for several yrs. Humidity of microclimate appears to be more important than over-all climate.[37] Weather determines effectiveness of fungus disease.		Do not like dense, damp fields.[38]	Cultural practices. Grow non-grass crops during yrs. of outbreak. Winter-burn hibernating regions--although this method probably only destroys 25-50%. Dieldrin gives better control than creosote barrier.[39]
European Corn Borer (*Ostrinia nubilalis*)	A variety of herbaceous plants such as corn, potatoes, beans, celery, gladioli & many weeds. Prefer older plants.		*Lydella stabulans grisescens* (may attack 45-70% of corn borer larvae) *Macrocentrus gifuensis*	Fungus disease, *Beauveria bassiana* (but disease often comes from lab-induced infection).	Dry summers and/or heavy rains at time of hatching unfavorable to insect.	Overwinters as caterpillar in plant stems. Extremely cold winters unfavorable to borer.	Two borer growth-inhibitors in tissues of young corn plants decline as plant grows older. Therefore, larger, more mature plants more attractive to ovipositing borer moths.[40]	Cultural & chemical.

Table 4-2

Insect Constraints (Cont.)

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Japanese Beetle (*Popillis japonica*)	Roots of grasses and vegetable plants		*Tiphia vernalis*, a wasp which attacks grub stage. One survey indicated av. of 43% parasitized.[41]	Milky disease	Amount of summer rainfall determines pop. changes: low rainfall --- high mortality of eggs & grubs & low beetle pop. the following year.	Grubs may take 2 years to develop in wet, cold soils.		Milky disease is man-induced. Chemicals. Cultivation kills grubs.
Gypsy Moth (*Porthetria dispar*)	Feed at night upon foliage of evergreen & deciduous trees & shrubs.	Several insect-eating mammals such as short-tailed shrew & deer mouse.	Effective parasites have been imported and are well established in N.Eng. Egg parasite: *Anastatus disparis*. Larval parasite: *Compsilura concinnata*. Pupal parasite: *Sturmia scutellata*.	Virus	High humidity and/or rainfall associated with virus epizootics.[42]		Efficacy of predators depends on existence of deep, moist forest floor that attracts these insect-eating mammals. Defoliation extensive when forest is open & dry. Area usually has history of frequent fires, usually light, sandy soil, little litter. Forest usually composed of birch, aspen or oaks.[43]	Chemicals before or shortly after eggs are hatched. Environmental control such as forest floor, mixed forest.

Table 4-2

Insect Constraints (Cont.)

Insect	Preferred Food Supply for Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Migratory Grasshopper (*Melanoplus bilituratus*) Differential Grasshopper (*M. differentialis*) Clear-winged Grasshopper (*Camnula pellucida*)	Differential esp. destructive to corn. Most have diverse feeding habits.	Rodents & birds.	Larvae of parasitic fly, *Trichopsidea clausa*. Maggots of flesh flies may be effective enough to decrease egg-laying adult pop. before summer. Maggots of bee flies, blister beetles & ground beetles attack grasshopper eggs & have been known to destroy 40-60% of eggs in wide area.[44]	Migratory less susceptible to fungus or bacterial diseases than differential. Fungus only effective when humidity is high. When temp. is high, grasshoppers tend to be susceptible to septicaemia.	Damage greatest in areas where rainfall is less than 25" annually. Migratory & clear-winged grasshoppers survive drought well. Differential does not. Most feed at temp. between 65-90° F. Weather factor most important from hatching through nymphal stage & early adult stage (Apr-July). Weather causing high mortality: warm spring (premature hatching); low temp. later (prevents dev. of any that hatched); long periods of cloudy, wet weather (encourages diseases).[45] Stay on ground during cool, cloudy weather. seek shelter if temp. drops below 68° F. Extreme drought leads to lack of food and rise in mortality.		Migratory prefers light, sandy soils. In dry years differential lives in irrigated areas & along streams.	Poisoned baits. Dieldrin & other sprays more effective than baits. Plowing to destroy eggs in fall & winter
		During a 10-yr. study in Mont. & N. Dak. about 20% of eggs destroyed by predators. 60% died soon after or during hatching period. 5% of older nymphs or adults killed by disease & parasites.[46]						

Table 4-2

Insect Constraints (Cont.)

Insects	Preferred Food Supply of Larvae	Predators	Parasites	Disease	Humidity, Rainfall, Summer Temperature	Overwintering (Temperature)	Physical Conditions	Human Intervention
Wheat Stem Sawfly (*Cephus cinctus*)	Feed within stems of small grains.		*Collyria calcitrator* and *Pleurotropis benefica* found to cause substantial pop. control of European wheat stem sawfly in Canada.[47]					Cultural: plowing under after harvest Crop rotation using plants that are not hosts to insect. No insecticide.
Wheat Jointworm (*Harmolita tritici*)	Feed within wheat straw as larvae. Usually pupate in fall.		In Oregon, insect found to be attacked by at least 5 parasites, but 2 account for 95% of parasitism.[48]					Cultural. No practical control by insecticides.
Colorado Potato Beetle (*Leptinotarsa decemlineata*)	Leaves & terminal growth of potato plants.							Chemical sprays.
Potato Leafhopper (*Empoasca fabae*)	Feed upon underside of leaves of potato and alfalfa plants.					Cannot stand cold. Seem to overwinter in South & migrate to North in spring.	Prefer mature potato plants.	Chemical control.

relationship between trees and insects feeding thereon could be correspondingly persistent. Silting of irrigation channels or dams due to erosion (see Section 7 of this chapter) could lead to the creation of swampy areas favorable to mosquito breeding. This has happened historically in various places such as the Pontine marshes at the mouth of the Tigris-Euphrates into the Persian Gulf and elsewhere.

Another potential threat is that heavy postattack emphasis on meat production to minimize the dietary Sr-90 hazard (see Chapter I) could conceivably lead to overgrazing. This could result in conditions favoring outbreaks of graminivorous insects such as grasshoppers and Mormon crickets. These insects prefer to lay their eggs in bare patches of hot, dry soil amidst patches of vegetation for food supply. A population density of 25 per square meter may consume as much forage as 33 cows per 100 acres. Distribution of grasshoppers in 1962 (a bad fire year, due to unusual dryness):

Grasshopper Population: 1962[49]

320,000	mi^2	with	3-7	grasshoppers	/yard^2	(average	4)
80,000	"	"	8-14	"	"	("	10)
40,000	"	"	15-27	"	"	("	20)
10,000	"	"	28+	"	"	("	30)

The above tabulation probably accounts for all grasshopper damage of a level sufficient to be counted, although there were probably 500,000 square miles with an average of 1-2 grasshoppers per square yard. On this basis the areas with abundant or very abundant populations (15 or more) accounted for over 30% of all assessed damage. Since insecticides were used against the heaviest outbreaks, it can be safely assumed that in their absence the damage would have been higher. Thus, conservatively it seems reasonable to assign one third of the total destruction to epidemic outbreaks and two thirds to endemic populations. The damage-frequency distribution is qualitatively similar to the distribution proposed (Appendix F) for destructiveness of fires. Quantitatively, the annual loss to rangeland (excluding croplands) due to grasshoppers alone is estimated to be $90,000,000[50] or 18% of the actual annual production from grazing land.

These figures apply, of course, to "normal" times without overgrazing or extra stresses. It is difficult to hold down the losses because many semi-arid lands vary widely in productivity from year to year (depending on whether rainfall is above or below average), thus providing the basic preconditions for violent fluctuations among local animal and insect populations. (Two high rainfall years in a row are likely to produce a population "explosion" followed by a sudden collapse.) A greater sustained human demand on the production of the land leaves less surplus for other species and may conceivably intensify the oscillations causing higher average percentage losses.

Past experience provides some indications of the nature and scale of future threats. Table 4-3 summarizes a few case histories of some interest in this regard.

Table 4-3

Periodic Insect Outbreaks

Species	Dates & Places of Outbreaks	Conditions for Onset	Control Measures
Chinch bug[51] (*Blissus leucopterus*)	1783- first recorded outbreak in U.S. 1850- 1900 U.S., $350,000,000 damage 1914- 13 Illinois counties (caused loss of $6,000,000 worth of corn, wheat, and oats. 1934- Illinois, $40,000,000 worth of damage 1963- (Sept.) Louisana The chinch bug has been found throughout the U.S., in southern Canada, in Mexico and in Central America. Its areas of greatest destructiveness are in the Mississippi, Ohio, and Missouri River Valleys.	70°F. temp. on sunny days. Invades at time of smallgrain harvest.	Heavy rainfall. Sowing of wheat on fertile soil (bug avoids shade & dampness). Winter burning in hibernating quarters in areas west of Mississippi River. Trapping and spraying barrier strips with dieldrin or creosote.
Engelmann Spruce Bark Beetle[52] (*Dendroctonus engelmanni*) Hopk	1898- White River National Forest, Colorado 1909- Lincoln National Forest, New Mexico 1939- 1950-S.W. Colorado	Trees blown down. Attracted by fermentation in cambium of unhealthy trees.	Woodpeckers, cold winters, sun curing, logging damaged trees. Normally repelled by pitch flow of healthy trees.
Fir Engraver Beetle[53] (*Scolytus Ventralis*)	1954- Cibola National Forest, New Mexico 1962- California (statewide)	Lowered resistance of trees due to drought periods	Predators: clerid beetles Parasites: braconid wasps and a mite (*Pediculoides ventricosus*) Oil spray & logging damaged trees.
Spruce Budworm[54] (*Choristoneura fumiferana*)	1909- Quebec 1910- 1925-forests of eastern U.S. and Canada Almost continuous outbreaks in Canada & U.S. have spread into Oregon, Minn. etc. Epidemic proportions reached in Ontario 1935--some decline since 1948. 1949- New Brunswick 1962- Warner Mountains, Modoc County, California	Overmature trees Dry, sunny summers for about 4 consecutive years.	Parasitic wasps and flies, logging damaged trees Birds Storms
Douglas Fir Bark Beetle Beetle[55] (*Dendroctonus pseudotsugae*)	1933- Tillamook Forest 1962- Shasta County, Black Mountains, Humboldt County, and Hatchet Mountain, California	Windthrown trees Fire-damaged trees	Mist of 5/ DDT in fuel oil, logging damaged trees

Table 4-3

Periodic Insect Outbreaks (Cont.)

Species	Dates & Places of Outbreaks	Conditions for Onset	Control Measures
Lodgepole Needle Miner[56] (Recurvaria Milleri)	1900-Southern Sierra Nevada 1945-Yosemite National Park 1955-Tuolumne River Basin, Merced River headwaters, California 1962-Kings Canyon National Park, California	Old-overmature stands Elevations between 8,000 & 10,000 feet	Disease: granulosis virus Aerial applications of malathion or DDT Logging timber
Hemlock Sawfly[57] (Neodiprion tsugae)	1933-Coastal forests of Oregon, Washington, British Columbia and Alaska	Old foliage	Hymenopterous parasites (Delomerista diprionis Cush. and Itoplectis Montana Cush. DDT and other chlorinated hydrocarbon insecticides
Sawfly[58] (Neodiprion taedae linearis)	1940-first observed in S. Arkansas 1945-48 3 million acres in that area attacked (loblolly and shortleaf pine)		Polyhedral virus (destroys larvae) Aerial spraying DDT in fuel oil
Western Pine Beetle[59] (Dendroctonus brevicomis)	1920-observed in the Pacific 1921-1946-Pacific States-25 billion board feet of timber killed. 1962-California (heavy in Southern portion of state) "Mother Lode" infestation--estimate acreage: 2,400,000--from El Dorado, south to Kern County, California Mostly attacks ponderosa and Coulter pine		Logging damaged timber Spraying infested trees: 5% DDT in fuel oil Inactive in temperature below 50°F.
Grasshopper[60] (Dissosteira longipennis)	1740-Massachusetts Colony 1805-Montana 1818-Minnesota 1874-76-swept across western plains states* 1891-95-(1892 peak) same area 1934-38-(1938) peak) " "	Several years of drought Subhumid and semi-arid regions Mountain meadows, and cutover land	Insecticides: aldrin, chlordane, heptachlor, methozychlor Tillage and seeding program

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The invasion caused over $200,000,000 damage and was termed a national disaster by Congress.

Table 4-3

Periodic Insect Outbreaks (Cont.)

Species	Dates & Places of Outbreak	Conditions for Onset	Control Measures
Differential grasshopper[61] (*Melanoplus differentialis*)	1939-observed in Mid-Western States* 1945-peak in Mid-West 1951-lower Yellowstone River 1955-McCone County, Montana and Sargent County, N. Dakota, Eastern Kansas	Above normal precipitation for an area, followed by lush growth. High temperatures (>80° F.) stimulate flying and migration	Poison bait Aerial spraying
Mormon Cricket[62] (*Anabrus Simplex*)	1848-Great Salt Lake Basin 1937-Rocky Mountain Region 1939-Nevada 1937-1949-Nevada, Montana, Wyoming, and Idaho	Migrations take place on clear days with air temperature 65°-95°F. & soil-surface temperature 75°-125°, when wind velocity <20-25 m.p.h.	Poisoned bait Oil and fence barriers Abnormally cold & wet weather for about a month Predators & parasites

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* Replaced migratory grasshopper in predominance from 1939. Replacement associated with higher precipitation.

In summary, the aftermath of a large-scale perturbation such as nuclear war may well lead to certain imbalances or temporary changes in the role of insects in the balance of nature as we know it. For reasons described, grasshoppers and forest pests are a particular threat if more favorable breeding conditions for them result from changed agricultural objectives and practices. In marginal subhumid grasslands subjected to overgrazing, or in radiation-damaged conifer forests, there would be considerable likelihood of pest outbreaks on a large and perhaps unprecedented scale. Elsewhere there is little reason to expect major long-term changes in the total amount of insect life in most biomes.

a. Rodent and Bird Pests

Assuming that the direct (e.g. radiological) environmental pressure on vertebrate populations was not overwhelming, postattack circumstances can be envisioned where animals or birds such as cotton rats, rabbits, hares, prairie dogs, ground squirrels, gophers, field mice or quail (bobwhites) erupt in enormous numbers, as they periodically do in normal times. In such outbreaks local areas are sometimes devastated--nearly 100% of all green forage produced can be consumed by starving rodents. Table 4-4 summarizes some cases of historical interest. As mentioned earlier, in connection with grasshoppers, greater stress on semi-arid lands, e.g. overgrazing, might possibly enhance this tendency by resulting in the creation of more favorable breeding grounds. Elimination or reduction of predators might increase the chances of such an outbreak also, although there is no obvious way this might occur. The various interactions controlling mammal populations ought to be studied more carefully.

The reproductive capacities of rodentia* are legendary--and perhaps somewhat exaggerated. Nevertheless, a population increase by a factor of 20 in a single season would be well within the realm of possibility, given ample food and protection from enemies. They eat leaves, roots, bark, seeds and fruit. Of all the animal species on earth, rats and rabbits are the most persistently competitive with humans, being resourceful, almost impossible to eradicate, and capable of adapting successfully to almost any environment.[63] The proven capacity of rodents to learn by example to successfully avoid disguised dangers (such as poisons) might or might not also enable them to avoid the worst of the radiation hazards.

It is a moot point, in many cases, whether birds do more harm than good, even when they feed largely on insects. Since birds are rather indiscriminate in selecting insect food, they often consume beneficial insect predators, such as dragonflies and lady beetles, proportionately as often as, or more often than, insect pests. Predaceous insects are frequently larger, and therefore more tempting to birds, than their prey. (On the other hand, parasitic insects tend to be smaller and correspondingly less tempting to birds.) Unfortunately, little is known about these complex population interactions. Fears which have been widely expressed regarding the ecological consequences

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*For convenience we include rabbits in the rodent category, though modern authorities class them separately.

Table 4-4

Vertebrate Pest Outbreaks

Species	Dates & Places of Outbreaks	Conditions for Onset	Control
Rat/Quail[64] Rattus spp. Celinus virginianus	Intervals of 12-13 years Peaks: 1911 or 1921, 1923 or 1935--Ohio. Northwest Texas--twice in last 25 years.	Unusually high rainfall followed by lush vegetation.	
Field Mouse &/or Vole[65] Microtus spp.	United States: large outbreaks in Humboldt Valley 1889-92, 1899-1901 and 1907-8. In 1907 destroyed 15,000 out of 20,000 acres of alfalfa. 1926 Kern, Calif. Density in center of infestation 17 mice per square yard or over 80,000 an acre.[66] Germany: 1878-9 especially forests in East Prussia and Schleswig-Holstein. 1917-18. Germany, Luxembourg, Holland, Great Britain and Hungary voles abundant in 1930. Russia: 1925-6 infested over $2\frac{1}{2}$ million acres in N. Caucasus steppes, 1927-heavy infestation in Ural region and the Ukraine. 1932: In Nov. $9\frac{1}{2}$ million acres in N. Caucasus. By Dec. almost 25 million acres in U.S.S.R. infested by rodents.[67]	Availability of large fields of cultivated crops such as alfalfa, hay, and potatoes. Shade trees. In 1925 crops had been planted in dried-up lake reservoir.	Predators: owls, hawks, fox Plagues may have ended because of spontaneous epidemic or because of heavy rains.

of widespread destruction of birds are apparently based on little more than sentiment or conjecture.

To the extent that birds eat seeds and fruit from cultivated fields or orchards, they are unquestionably pests; but, again, the same birds also eat large quantities of the seeds of undesirable plants such as ragweed. Farmers of the older generation often take an uncompromisingly irrational negative view of the activities of birds while Audubon groups tend to incline the other way. The pro's and con's cannot be weighed with complete objectivity, although the prevalent view is fairly "soft" on birds.

The vulnerability of mammals and birds to fallout radiation will depend on both radiosensitivity and exposure. These factors were discussed in Chapter I. One serious consequence of β-radiation to wild animals and birds could be the loss of fur or feathers, or burns to nose, tongue, or throat. Either might be fatal in a wild environment where invalids do not survive long.

Vulnerabilities might change somewhat with the seasons. In winter, most rodents live largely underground in tunnels or burrows where they would be fairly well protected. Many birds migrate during winter, but relatively few species actually leave the continental U.S.; many winter along the Gulf Coast.

b. Plant Pests (Weeds)

"Weeds" are defined as persistent herbaceous and broad-leaved plants of no positive value, or growing in the wrong places. In most cases they are transitory species, being followed in the succesion by grasses or shrubs and finally trees, as the case may be. At times certain vigorous species of nuisance plants have shown themselves capable of invading new territory on their own. For example, the prickly pear cactus introduced into Australia accidently, spread over (and ruined) 60 million acres of grazing land by 1930. Similarly Klamath-weed or goatweed, imported from Europe (where it was called St.-John's-wort) invaded 2.5 million acres of rangeland in the United States by 1950. In each case the weed was controlled by importing an insect from the weed's native habitat.*

There is no universal set of characteristics by which "weeds" can be distinguished from crop plants, except that of being unwanted. Hence one cannot analyze the effect of a thermonuclear war on weeds per se except for a simple remark: as a result of lack of cultivation weeds can be expected to increase vis-à-vis crop plants. This is not due to any special characteristics of weeds, however, but due to a characteristic of the cultivated agricultural ecosystem; namely, the system is not in its natural equilibrium, but in an artifical one maintained by the farmer's efforts.

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*An Argentinian moth, Cactoblastus cactorum, brought to Australia 1930, cut the prickly pear infestation by 95% in seven years. Two beetl Chrysolina gemellata and C. hyperici, imported from southern France between 1944 and 1948, had reduced the weeds by 99% in 1959 (to a stable residual population).

Without human interference the ecosystem returns to its natural state, in which weeds--as remarked above--have at least a transitory role.

In a certain sense weeds have an advantage in a postattack environment: weeds are nature's generalists, whereas crop plants are specialists. Generalists, it can be argued, are more adaptable to new situations than specialists; ergo, weeds are likely to become a greater nuisance in a postattack environment than preattack. To the extent that this is true, it is because the plants which profit as a result of environmental changes are more likely to be "weeds" than not. This is partly a consequence of the statistical fact that weeds include the vast majority of all species of higher plants, and partly because crop plants are highly bred to accentuate certain useful characteristics, but at the expense of the capacity to survive in a wild environment.

D. S. Grosch[68] has pointed out that weeds may serve one useful purpose in a postattack environment, namely as a disposable cover-crop. (Sod, which could be stripped off easily, might be even more appropriate.) A substantial percentage of the soluble radionuclides from fallout might be trapped by the foliage or root mat which could be "harvested" as a means of decontamination.

Another advantage of weeds (provided they are mixed) is that they are not likely to support epidemic level populations of any single insect pest or disease organism. Hence weed-grown fields would probably be stabilizing in at least one respect in the postattack world.

There is no apparent danger of a single obnoxious species, such as Klamath weed, taking over the richer farmlands and re-establishing a base where none previously existed. Actually, the likely weed species are all well-established and widespread already; and there are hundreds of them, no single one being dominant.

4. Microclimate

Long-term changes in the microclimate (i.e. the temperature, humidity and wind velocity near the ground) may be among the most important results of a thermonuclear attack. Generally speaking, the immediate cause would be destruction of vegetation by fire and/or radiation and/or insect disease outbreaks. Most likely, there would be multiple stresses acting in concert, a point strongly emphasized by Stonier.[69] Since forested watersheds undoubtedly have a very strong influence on the microclimate in a way in which farmlands, by and large, do not, most of the subsequent discussion will be concerned primarily with forests, especially coniferous forests.

Assuming, for the moment, a catastrophe (radiation/disease/insects/fire), resulting in the destruction or defoliation of our forests, one of the first effects on the microclimate would be higher ground and soil temperatures, and correspondingly lower humidity near the ground. Forests have an important cooling effect on the earth with ground temperature averaging several degrees cooler than those at the canopy level on a sunny day, and as much as 80° F. cooler than peak ground temperature would be in the absence of protective foliage. In the open, temperatures of soil, rocks and litter often reaches 160° F. when the air temperature is 85-90° F. See Figure 4.1, 4.2. (Soil temperatures would remain still higher after burning, the probable ultimate fate of many dead forests which are not harvested by man, since blackening and charring tend to increase heat absorption.) Several mechanisms are involved:

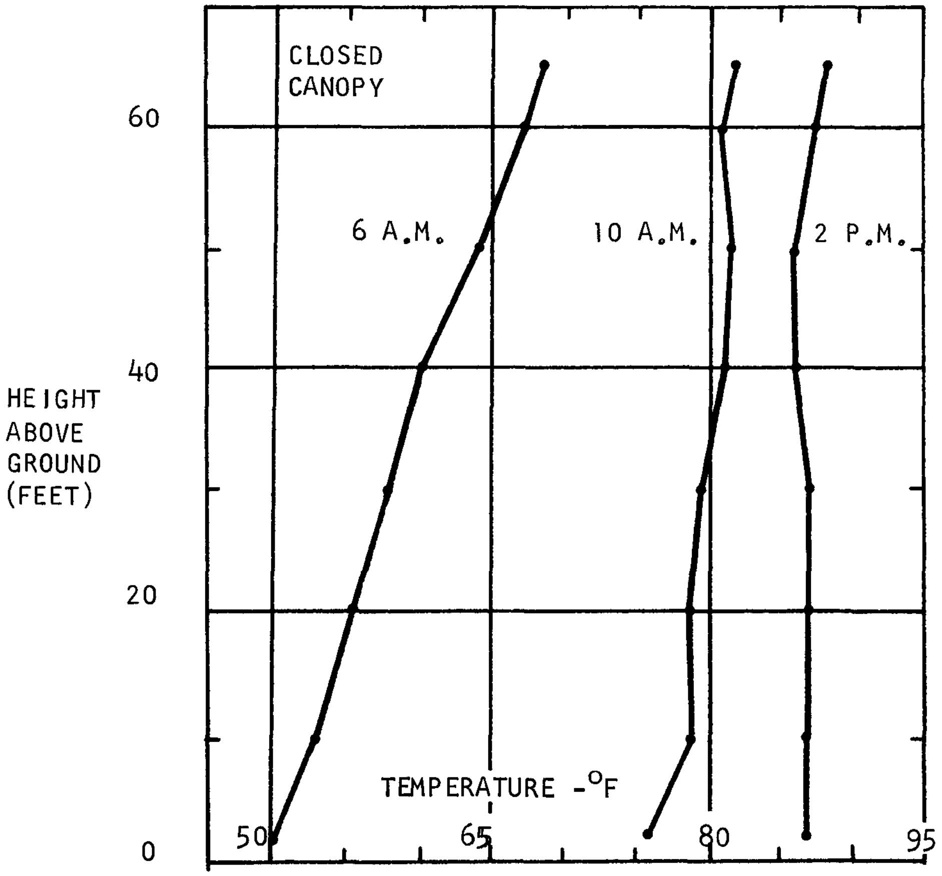
(1) Heat energy from sunlight is converted by photosynthesis into chemical energy. Relatively little sunlight reaches the forest floor, e.g. about 4% for a typical eastern deciduous climax forest (the experimental forest at Rutgers University).

(2) Little water is lost by runoff even during wet periods. Perhaps 1% of the rain strikes the floor of a dense forest directly. Water soaks into organic material (e.g. the bark of trees, underbrush and dead leaves, etc.) or is trapped by the roots in the soil. Instead of escaping into rivers, lakes or ground water, it is available for use in dry periods when it is evaporated (transpired) from the surfaces of the leaves. This evaporation is the principal cooling mechanism (similar to perspiration for humans). Humidity at the forest floor may be three times as high as it is above the canopy (on a dry, warm day) as a result of evaporation.

The destruction of forested areas as a result of thermonuclear attack would evidently cause (1) higher ground temperatures and (2) less evaporation, over wide regions, since more of the water would run off on the surface after rains. Opinions vary as to whether this would in turn affect the climate (macroclimate); some have argued that it would, citing changes from wooded to desert country which have this occurred in North Africa and elsewhere in historic times.[70] On the other hand most meteorologists seem to believe the contrary, pointing out, for example, that only 10% of the rain which falls on this continent originally evaporated from the land surface.[71]

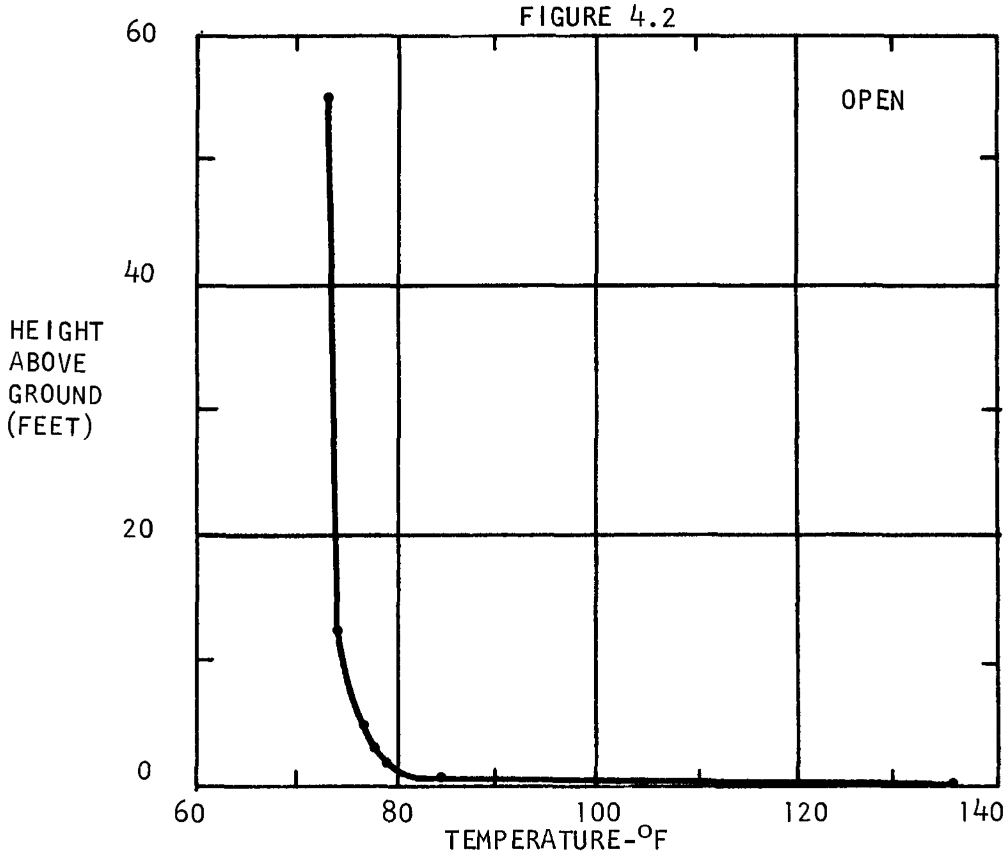
TEMPERATURE PROFILES[2]

FIGURE 4.1



TYPICAL TEMPERATURE PROFILES IN A DENSE MIXED-CONIFER STAND SHOWING THE PROGRESSIVE DOWNWARD TRANSFER OF HEAT INTO THE STAND FROM THE CROWNS

FIGURE 4.2



TYPICAL NOON TEMPERATURE PROFILE OVER BARE GROUND IN THE OPEN

Furthermore, in many regions transpiration is not presently an important factor; i.e., in Utah 90% of the precipitation re-evaporates before it can be removed by runoff (95% in summer, 85% in winter), regardless of vegetative cover.

In the last century there have been some attempts to carry out controlled experiments to elucidate the question. One such experiment was carried out in central India in connection with a reforestation project, though the results were indeterminate because of coincidental climatic changes. A careful series of observations in Germany (1937) indicated that about 6% of the rainfall on the Letzlinger heath is traceable to the effects of reforestation.[73] A less careful set of measurements was made in the Congo (1934) which, however, gave more dramatic results: namely, that in the virgin forest, rainfall was 30% higher, humidity averaged 15% higher, and temperature 1.5% lower than in surrounding unforested areas.[74] Other measurements have been made over smaller areas (Tennessee Copper Basin, Wagon Wheel Gap in Colorado) in the United States.[75]

The fundamental question seems to be whether a denuded area of wide extent would produce the sort of updrafts which lift moisture-laden air into regions of low pressure where adiabatic cooling (and condensation) can take place. There is no consensus on this point at present, although the weight of the evidence seems to point toward a modest, but real, drop in total rainfall coupled with slightly higher atmospheric temperatures.

Without taking into account secondary fires and early melting of snowpack, the situation as seen by W. Criddle, Utah State Water Engineer, is as follows:[76]

(1) Assuming pine-spruce-aspen forests at high elevations were killed by radiation, fire, insects, etc., total runoff would increase but the rate would not change significantly due to protection of the ground by vegetative litter (pine needles, etc.).

(2) Assuming piñon-juniper on lower slopes were killed (but did not burn), total runoff would again increase and the ground water level would also be improved.

Of course, fire is a serious possibility if large areas of forests have been killed by radiation or beetle outbreaks facilitated by radiation injuries (section 5). In densely forested areas such fires could be extremely hot, destroying much of the organic ground litter and humus. In less densely wooded regions, fires would probably be more similar to the brush fires which occur regularly after droughts. Criddle estimated that runoff would again be increased in both cases and that serious erosion might also occur on the lower (piñon-juniper) slopes (section 7).

Another significant consequence of removing vegetation is that the ground surface and litter is more exposed to the drying and eroding effects of the wind. In a dense climax deciduous forest, wind velocity on the forest floor averages as little as 3% of the velocity above the canopy. In western conifer forests the figures average somewhat higher (10-20%) depending on type, but still the windbreak effect is quite appreciable, as Figure 4.3 illustrates.

It was pointed out above that loss of forests would certainly result in less evaporation. A corollary of this is that water available for runoff would be correspondingly greater. While too much runoff causes erosion, floods, and other undesirable consequences (see section 7), too little is also awkward in country where water is scarce and must be utilized with maximum effectiveness. In fact in Utah, Texas, New Mexico and California, it is standard practice to poison, uproot or burn stands of native chaparral and other woody brush to facilitate the growth of range grasses. It is found by experience that the result is usually to increase the amount of ground water available (the water table rises), presumably because the shallow-rooted grasses prevent surface evaporation more effectively than brush or trees but do not draw water up from deep below the surface in dry periods. The well-known salt cedar, a brushy tree which grows along stream beds and irrigation canals, is a particularly blatant water-waster. Where the water table is already high, as in Alaska, the destruction of trees can create swampy conditions. On the other hand, after vegetation is removed moisture retention is reduced in the upper layers of the soil in most cases, because direct rainfall, uninterrupted by foliage, causes soil compaction. Burrowing species of soil fauna may also be substantially cut in number. Reduction of humus content (see section 6 of this chapter) can be correlated with lower water-holding capacity, sometimes for as long as 50 years after a fire.

We have already noted two contradictory results of increased runoff:

(1) more water for irrigation (if storage capacity exists), less loss by transpiration, higher water table;

(2) less water soaking into the ground, lower water table, too much water in rivers (leading to erosion, floods, etc.).

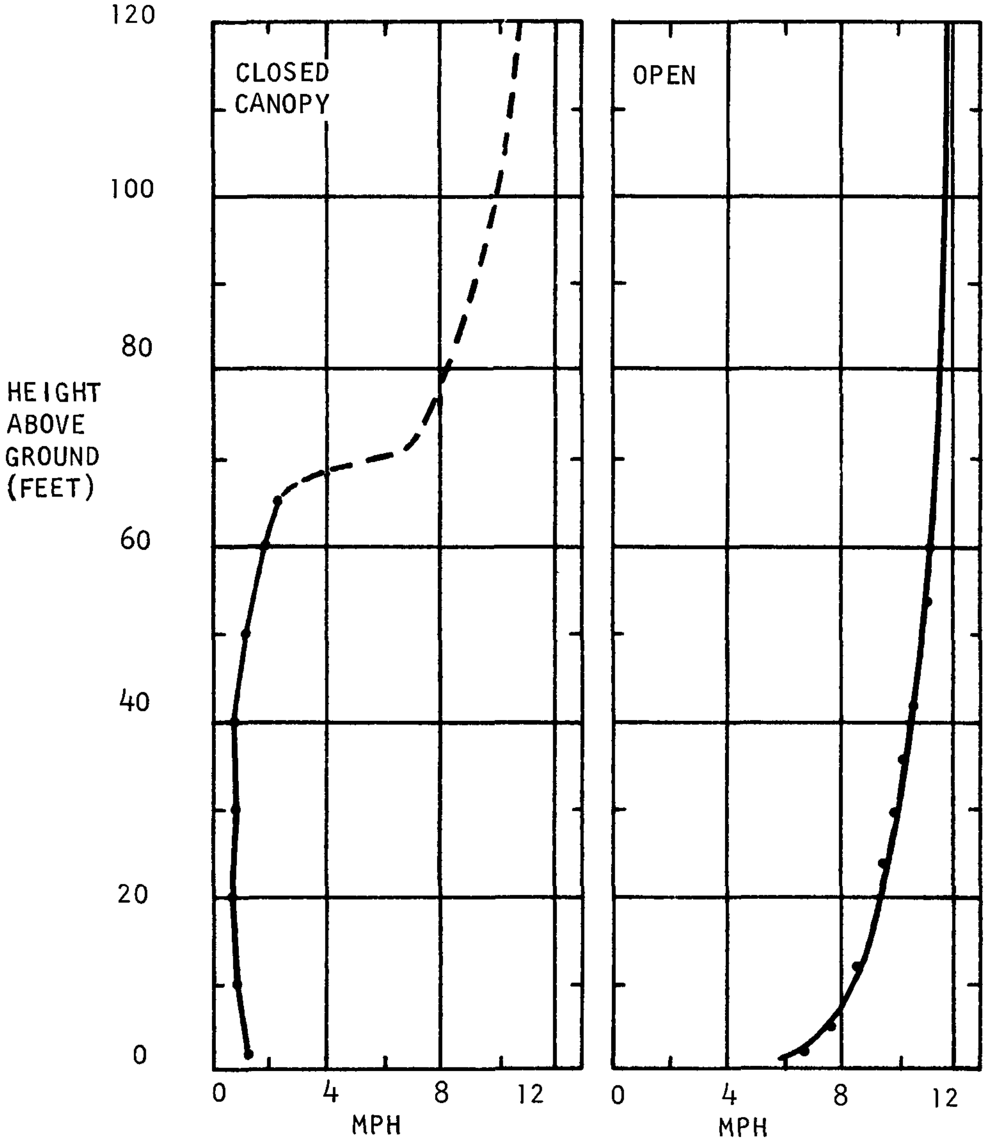
The first result is typical of quite dry areas where loss by evaporation is a greater problem than runoff; in fact the runoff itself often evaporates. Fire is often used deliberately to increase runoff, as remarked in the previous section. The second result is typical of areas where the priorities are reversed: evaporation is not a problem but runoff is. Class (1) areas include the watersheds of the Rio Grande; the Colorado and the interior drainage area of Nevada and Utah. Class (2) areas include all the other watersheds of the U.S., notably the Mississippi and the Columbia. Figure 4.4 shows the major regions on a forest map.

The "forests" of Class (1) areas are not particularly attractive targets to an enemy, for they are not important assets. From the agricultural point of view, as noted above, we would certainly be better off with grass in place of yucca, juniper, chaparral, piñon, salt cedar, creosote bush, sagebrush, mesquite, etc. More water would become potentially available for irrigation. As far as lumber is concerned, the areas in question are too dry to be highly productive, and generally too remote to be economically worth exploiting.

Changes in the microclimate would evidently have an influence on the incidence of secondary fires, and on problems related to soil and water conservation. With trees and undergrowth dead, in most cases organic litter protecting the soil surface would either dry out and burn or eventually be removed in many areas by the combination of wind, rain, and runoff from surface water which does not soak into the ground because of mechanical compaction of the unprotected soil. Secondary fires are discussed in section 5 and erosion in section 7 hereafter.

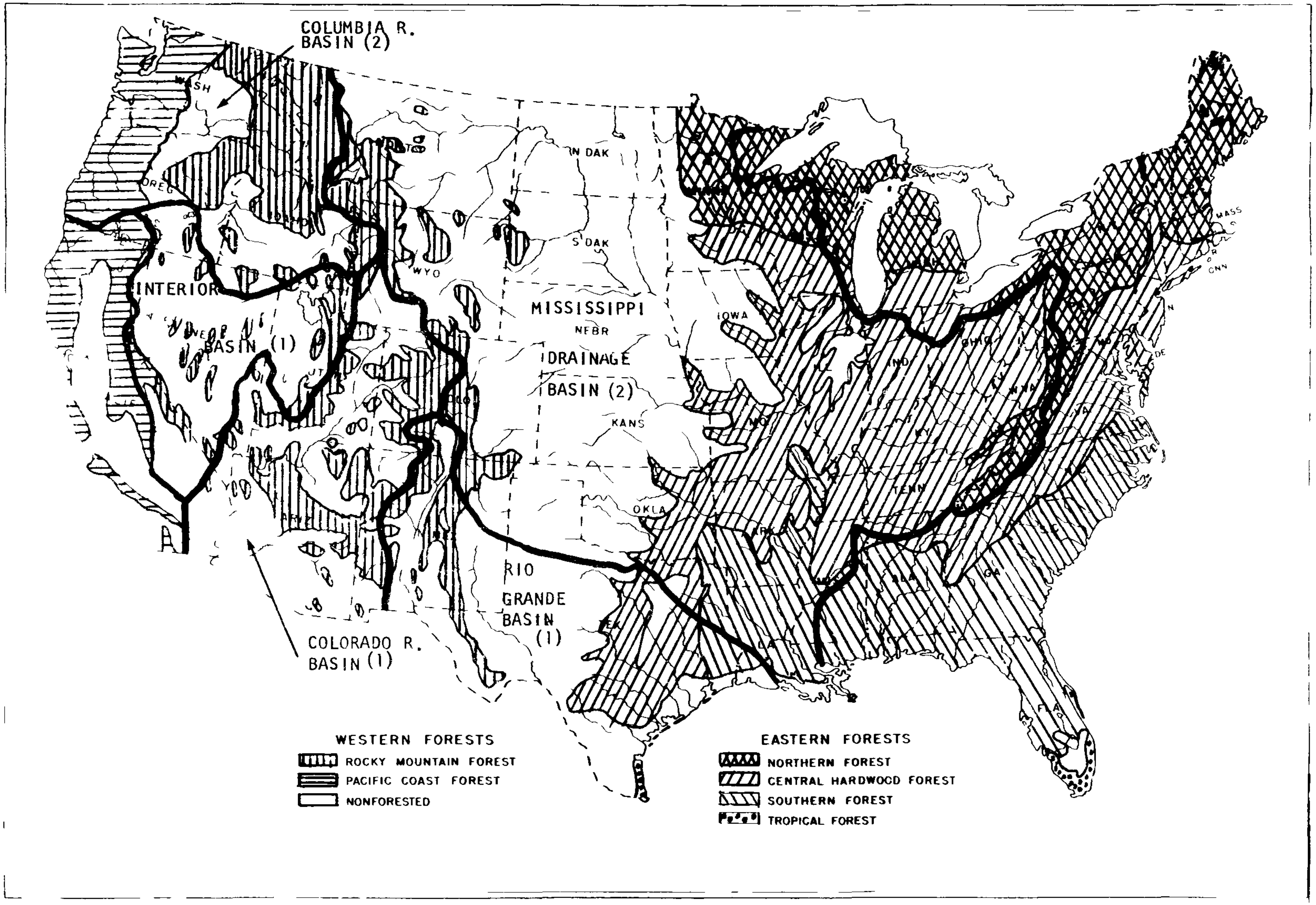
FIGURE 4.3

WIND PROFILES[77]



LEFT, TYPICAL DAYTIME WIND PROFILE IN AND OVER A DENSE CONIFER STAND; RIGHT, TYPICAL DAYTIME WIND PROFILE OVER LEVEL GROUND IN THE OPEN

FIGURE 4.4
FOREST REGIONS OF THE UNITED STATES



5. Secondary Fires

In our terminology, secondary fires are ignited by natural causes (e.g. lightning) in areas where there is much dead vegetation. The original damage may be due to radiation or, more likely, radiation plus disease or insect attack. The slash fires around lumber camps which often got out of control in the 19th century, and which initiated most of the so-called "catastrophic" fires listed in Table 4-5, page 55, were essentially secondary fires in the sense that most of the fuel was already dead.

The major difference between the potential forest fire hazard in areas of dead vegetation and the normal situation is that the probability of ignition and the probable degree of spread are greater. Where foliage is removed, the material at ground level is exposed to the drying action of sun and wind. Average temperature near the surface may rise far above the ambient* temperature of the air. Average humidity near the surface may drop from close to 100% to well below ambient levels (depending on the area), and wind velocity at ground level may increase from as little as 3% of ambient under a dense canopy to 50% or more when the foliage is removed. This was discussed in section 4, above. See, particularly, Figures 4.1, 4.2 and 4.3.

Not surprisingly, the drier fuel is easier to ignite and burns faster. The average state of affairs in an area of dead vegetation approaches conditions typical of extreme drought elsewhere. At least, extremely dry conditions occur much more often, perhaps after a week or two without rain, instead of the four to six weeks that it usually takes to produce an extreme fire hazard in a green forest.

The quantitative difference in terms of expected damage by fire may be estimated crudely from Figure 2.3, which suggests that slash fires will spread 6 times as fast as fires in mature timber under average California conditions and 2.8 times as fast under Idaho-Montana conditions. Another study found that under typical burning conditions (85° F. temperature, 15 mph wind velocity and fuel moisture of 4%, measured in the open) a fire starting on a moderate slope will burn 4.5 times as fast in the open as in a closed stand.[78] This comparison is probably a reasonable indicator of the difference to be expected in the two cases of green versus "dead" forests.

Inquiries put to several authorities in the field have tended to confirm these numerical estimates. A fire spread ratio of "at least ten to one" was predicted by one expert, who commented further that a green cutting line is often used as a firebreak because of its natural resistance to ignition.[79]

There are, however, a number of caveats which must be mentioned. In the first place, ignition in any forest--green or not--is likely to be from fire fuels such as dried grasses, leaves, needles, rotten "punk," or slivers of bark. While these are more abundant in a dead forest, they exist

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*Ambient temperature, humidity and wind velocity can be conveniently defined as the asymptotic values beyond the reach of surface effects, e.g. a few hundred feet above ground level.

plentifully in a green one. Since these kindling fuels tend to carry the fire as it spreads, the importance of the over-all proportions may be minimized in some cases. However, to the extent that the principal cause of ignition is lightning--as in Montana--the proportion of dead snags to live trees would strongly influence ignition probability. Many live trees do not ignite after being struck, but a snag would be most unlikely not to burn. In this regard, also, defoliation can be a two-way street. Some fires get started in rotten logs or debris and smoulder on the ground, protected for long periods from undue wetting by the dense canopy overhead. When conditions are ripe such "sleepers" may flare up and spread. On the other hand without the umbrella of protective foilage the chances of the embers remaining "alive" might have been substantially lessened.

Further, some types of conifer forests are more subject to crown fires, spreading from treetop to treetop, than to ground fires. When such forests are defoliated they may become less rather than more imflammable. They may help to explain why fire damage in the Engelmann spruce forests of Colorado did not noticeably increase following the disastrous bark beetle epidemic of 1938. On the other hand, in the more open ponderosa pine stands of California the "expected" pattern was more nearly confirmed after an insect epidemic on the Modoc Plateau. Apparently, after the trees had been dead for some time and had begun to shed their bark and develop rotten spots, fires from any cause would run up the trunks. Burning embers carried by the wind could ignite other trees up to a quarter of a mile away.[80]

It must be noted, finally, that deciduous forests are <u>normally</u> defoliated (although not necessarily dehydrated) for half the year. Fires in such forests are known to be harder to control without the presence of foliage than when the trees are in full leaf, although seasonal factors may be partly responsible.

In conclusion, it is probably fair to say that the over-all fire hazard (exclusive of primary ignitions) in damaged areas would probably increase several-fold over the current peacetime level. In 1962 (a bad year) approximately 16,000 square miles burned in the United States. This was only one-fifth of the 1930 and 1931 figures, also bad fire years. The difference is partially attributable to relatively permanent changes (e.g., firebreaks, better forestry practices) and partly to better fire spotting, fire control and fire-fighting techniques. Some of the latter might be initiated by disorganization, demoralization or shortages of men and equipment in a postattack situation. The "potential" for a postattack year of extensive drought, might be 40-50,000 square miles, without allowing for the effects discussed previously in this section. If 20% of the total forested area were damaged or killed by one mechanism or another and if the fire-spread potential increased by a factor of 5 in such areas, we might expect as much as 100,000 square miles to burn later. The total seems more likely to be smaller than greater, since we have made generally pessimistic assumptions. Nevertheless, the number is comparable with the 1930-1931 figures.

Of course, if 50% of the forests were defoliated by multiple insults as a result of a really massive nuclear attack, then on the same basis 150,000 square miles might conceivably burn in a year. This would represent about 15% of all forested land in the United States. It is difficult to imagine circumstances under which the percentage might be much larger.

6. Problems of Ecological Succession

We have had some experience of the ecological effects of fire, most of our present ecosystems having been affected to a greater or lesser extent by past fires. Succession following other types of extended damage--insofar as we have any basis for comparison--seems to follow similar patterns. Consequently, to the extent that the effects of mass fires of the past are similar to the effects which can be expected to result from fires caused by thermonuclear attack, there is a fair amount of recorded experience upon which to draw. The consensus of opinion, as we have noted elsewhere, is that there will probably be relatively little difference, except in scale, in the two cases. However, where both fire and fallout occur together or sequentially, the effects on wildland ecosystems may be magnified.

Soil erosion is the most serious long-term consequence, because all terrestrial ecosystems are dominated by plants,which provide the basic food for animals and man, and these plants cannot exist where the soil is removed. The extent and amount of erosion that will occur depends upon the terrain, type of soil and vegetation, and the rapidity with which the area is reinvaded by plant life. (See section 7 of this chapter.) In addition to these factors, which are a function of the area, much depends (at least in principle) upon the extent of the area which is burned over and the intensity of burning. The latter depends upon the nature of the fire, i.e. whether it is a conflagration or firestorm. Insofar as mass fires are of the moving front, conflagration type, it would seem that peacetime fire experience should provide a good guide to the probable aftereffects of fires caused by thermonuclear attack. Even though such a fire may have thousands of ignition points and will burn over a larger area, the duration of the active burning phase in any one area should be of about the same as in another. However, if a firestorm should develop, the ecological effects may have no direct parallel in past experience. The few firestorms which have been recorded were in urban areas, as a result of incendiary bombing or, in one case, an atomic bomb (Hiroshima). Many forests do not provide a density of readily combustible material comparable to that of a city and apparently required for a firestorm. However, there may be some forested areas with sufficient fuel density to support a firestorm, given the proper weather conditions and many simultaneous ignitions over a large area. The expected result of a firestorm is not only substantially complete burning but also the concomitant destruction of many life forms to a considerable depth beneath the surface. Porosity of the soil may be reduced by destruction of insects, earthworms, and microorganisms which normally channel the soil. Further compaction of the soil could occur as a result of being more completely exposed to the heat of the sun. Potential sources of regeneration, e.g. seeds, spores and eggs, may be killed. The chances of unburned refugia remaining approach zero. In short, the entire area may be sterilized to a degree of which we have little or no previous experience, thereby greatly inhibiting repopulation.

The effects of the more familiar type of fire vary widely from place to place and appear to be a function of numerous factors: topography, soil, type of vegetation and tree population, species of insect and animal life.

The very diversity of these factors and the resultant disparity of ecological effects make generalizations difficult. Comments with any degree of validity can be made only when considerable specific detail about a particular area can be given. Some examples of the way in which fire results in quite different effects on soil and living organisms will serve to illustrate the problem.

While it is often true that the consequences of fire are deleterious, so great is the variance due to topography, soil, and type of vegetation that in some cases burning either does not cause much damage or is actually beneficial. This is apt to be true under one or more of the following conditions: if the land is flat or gently rolling; if soil is exceptionally porous (e.g., sandy); or if the area has a potential for quick reinvasion by the prefire species or a more desirable one. The New Jersey or Southeastern pine barrens and some brushy wooded grazing areas in California suffer relatively slightly. In fact, fire is sometimes deliberately prescribed in these areas to reduce duff and litter, prepare the seedbed, and reduce competition from less desirable subordinate vegetable species.[81]

Fires over semi-arid grassland and range would almost certainly be more beneficial than harmful, biologically speaking. The Indians of the Southwest formerly burned the prairie regularly, and fire is increasingly being used again as a deliberate method of controlling the ecological succession of the range. Fire favors grasses against competing woody plants such as mesquite brush. Indeed, during the long period since grass fires have been more or less rigorously suppressed, mesquite has spread over 75,000,000 acres of former grassland. This land would be partially returned to grass in the event of widespread fires, since perennial grasses lose only a year's growth in a fire and produce plenty of seed in the first or second year following, while woody shrubs require several years after germination to produce seed. Grass is economically valuable as forage, whereas relatively unpalatable shrubs are virtually useless, besides more wasteful of ground water.

In support and extension of the foregoing, we may remark that there is one very general respect in which reversion to an earlier stage of succession, following fire or other damage, is more beneficial than not. It is an observed fact, of such generality as to approach the status of a law, that early succession ecosystems are more productive (of calories, edible protein or "biomass") than climax ecosystems.* This, by the way, is why agriculture depends upon early succession types--which would quickly be replaced by others if nature were allowed to take its course. The reason is, of course, that early succession types are fast-growing and short-lived, whereas climax types are slow-growing but long-lived.

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*Similarly, young plants (e.g. grasses) are more nutritious and palatable than old ones.

The texture of the soil may be unfavorably affected by heat. In some cases burned soil (especially clay) becomes harder and less permeable to water, due to partial baking ("colloidal aggregation"). Sometimes reduction of porosity is also ascribed to destruction (by heat) of insects, earthworms, and microorganisms which normally channel the soil.

Temperatures measured in various fires are given in Table 4-5. The dramatic differences between the measurements in different cases are probably mainly due to a difference in soil water content and in the length of the burning time, which depends on the amount and type of fuel available. A point to remember is that in most fires (but not necessarily in the case of a "firestorm") there is insufficient time for a steady-state temperature gradient to be reached. Therefore, a high temperature "pulse" is created as the fire burns at the surface, which starts (very slowly) to penetrate the soil. If the fire passes within a relatively short time, before the heat penetrates far, the surface cools down quickly by re-radiation. However, if a thick insulating layer of ashes is formed on the ground, the heat may be trapped. The greater conductivity of porous sandy soils is probably due to convection or "percolation" of hot air or water.

Soil temperatures stay higher after burning because of blackening and charring, which greatly increases heat absorbtion. At the surface, temperatures run about 20° F. higher on a sunny day, though at night they tend to be cooler due to correspondingly more efficient radiation. At a depth of one inch, under burned grasslands, minimum (annual) temperatures average 2° F. higher and maxima average 12° F. higher. At three inches depth (where the year-round temperature is more nearly uniform), both minimum and maximum average 4-5° F. higher. Temperature increases of a few degrees may affect vegetation quite seriously, i.e. seedlings and N-forming bacteria may be killed, spring germination comes earlier, etc.

Chemical changes due to heating do not fit any simple pattern. In some cases soluble minerals are released from ashes of organic materials, thus temporarily increasing fertility. In other cases growth-inhibiting compounds are apparently formed. Fairly general agreement exists to the effect that some heating (e.g. less than 200° F.) tends to be beneficial, at least to grasses and cereal grains. Certain pathogenic organisms (fungal spores, bacteria) are more easily destroyed by heat than the protected plant seeds. Some plant seeds, such as Rhus spp., germinate 17 to 60 times as well after heating.[82] Other pyrophilic species are Cheonathus, Rhamnus californica, Abies magnifica, Pinus ponderosa, Pseudotsuga taxfolia, and Avena.

Loss of humus is a normal concomitant of fires. In old pine or spruce forests there may be a very thick layer of needles, cones, etc., on the ground. Fires have been known to burn as much as two feet of this organic layer. Some relevant data have been collected by Daubenmire and by Ahlgren.[83]

Bacteria are influenced by the reduced acidity (pH) of soil after fires, due to the (temporary) release of alkalis from ashes. In most cases such effects seem to be very short-lived (of the order of one week), but in

Table 4-5

Soil Temperatures in Various Forest Fires*[84]

(in degrees Fahrenheit)

1.	Heavy forest fuels (Douglas fir, cedar, hemlock) in Western U.S.	1841 608	above the surface 1 inch in soil
2.	Heavy forest fuels (same as above)	850 120 60 75	above the surface under 3/4 inch of duff under 1½ inches of duff 1 inch in soil--no duff cover
3.	Long leaf pine (Southern U.S.)	150-175	under 1/4 inch for only 2-4 minutes, negligible rise in temperature under 1 inch
4.	Spruce and pine slash (Russia)	500	1/4 inch in sandy soil (Heat penetrated deeper in sandy soil than in heavy soils, in this fire.)
5.	Spruce and pine slash (Australia)	178-415 150	1/4 inch in sandy soil 1 inch in sandy soil
6.	Mixed chaparral of blue oak, dwarf interior live oak, wedgeleaf ceanothus, with scattered herbs (Calif.)	840 410 235	½ inch in duff ½ inch in soil 1½ inches in soil
7.	Common manzanita, scattered grasses and weeds (Calif.)	960 215	½ inch in litter 1½ inches in soil
8.	Light fuels, burning two hours (Sandy soils in a eucalyptus forest in Australia)	480 235 145 95 59 54	at surface 1 inch in soil 3 inches in soil 6 inches in soil 9 inches in soil 12 inches in soil

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*Variations and discrepancies in temperature figures in spite of similar vegetation and soil are due to different methods of measuring, seasons, weather conditions, type and quantity of dead plant material on the ground. These conditions were not specified in the citations mentioned above.

the Douglas-fir region slash burning with the subsequent release of calcium favors the growth of nitrogen-fixing bacteria Azotobacter and Clostridium.

In northern forests, Canada, Minnesota, mosses and lichens are destroyed by fires and recover very slowly. On the other hand, in some areas hand mosses and lichens are characteristic of post-fire successions. In the New Jersey pine barrens the burning of trees stimulated both mosses and lichens. In many cases plant diseases are checked by fires which destroy insect vectors or spores of fungi without killing the trees. For example, brown needle spot, Septoria acicula, in a longleaf pine is drastically reduced during the first and second years following a fire. On the other hand, certain diseases are favored by post-fire conditions. Fire scars on aspen, jack, red and white pine allow entry to heart rot, Fomes ignarius. Wood-boring insects which destroy the habitat of birds often increase after fires. Fire-damaged stands may serve as breeding grounds for insects or fungi, and disease resistance of trees seems to be adversely affected by heating soil above 250-300° F. In the top two inches of burned soil the population of invertebrates (insects and worms) may drop to as little as 10% of pre-fire numbers, depending on temperature. Earthworms are comparatively more susceptible than other species.

Vertebrates react variously. Deer prefer subclimax (e.g., post-fire) vegetation, as do grouse. Other species such as Caribou (in Canada) disappear following a fire. Small fires destroy relatively few individuals directly, due to burrowing habits or mobility. Some birds, e.g. wrens, quail, bluebirds, actually follow fires, nesting in fresh burns. Fires which destroy popular nesting places such as marshes, and especially if eggs and young are trapped, may lead to increases in insect activity. Squirrels often disappear from burned areas for ten years, as do beavers and other fur-bearing species. Mice, such as Microtus, require at least one year's mulch for runways. Controlled grass fires in longleaf pine woods help cut the rat population. Fish are often killed by the wash of ash into streams and ponds.

Plant species react very differently. Species-by-species analysis would be required. Definite patterns of post-fire succession exist, but depend on the climate, soil, surrounding vegetation, etc. Usually, herbs, grasses, and shrubs invade the burned area. Seeds may be windborne or long-dormant already underground (perhaps stimulated to germinate by the heat). Many brushy species sprout vigorously after fires from surviving roots. Seeds of other species are brought into the site by animals browsing on the plants which grow at first after the fire. Access of sunlight and removal of forest litter favors seedling growth for conifers as compared to deciduous species. The former are inherently faster growing but cannot penetrate litter due to shallow root systems and increased need for water. Hence deciduous species seldom follow burning.

Jack pine (*Pinus banksiana*) follows fires in the North, but is only moderately fire-resistant itself; seeds in cones remain viable for many years, cones being opened by heat. Jack pine prefers sandy soil.

Paper birch and white pine (*Pinus strobus*) often follow fires in northern Minnesota. Paper birch is easily killed by fire, while white pine is moderately resistant. These are normally succeeded by basswood, fir and black ash. White pine invades clay-loam sites. Paper birch likes mineral soil and plenty of sun.

Red pine (*Pinus resinosa*) seems to follow fire sometimes on sandy soil. Opinions differ on whether burning favors this tree. It is itself quite resistant to fire, having moderately high crowns, deep roots and growing in open stands.

Aspen (*Populus spp*.) is a well-known fire cover. Vegetative sprouting occurs in the first year following fire, and germination of seeds is very vigorous two or three years after a fire. Aspen is easily killed, due to thin bark. Stands are persistent, fairly dense, and hard to replace by other trees.

Black spruce (*Picea mariana*) is also highly susceptible and sometimes slow to return after fire. Heat destroys seed in the cones and reseeding requires wind or other mechanisms. Spring and early summer fires are the worst; later fires seem to be less serious and reproduction may be fairly rapid.

Longleaf pine (*Pinus palustris*) is exceptionally fire-resistant and fire can be used deliberately to favor this species. It has thick bark, very deep roots, high, open crowns and grows in very open stands. Other generally resistant species are pitch pine (*Pinus rigida*), pond pine (*Pinus serotina*), slash pine (*Pinus elliottii*), shortleaf pine (*Pinus echinata*), loblolly pine (*Pinus taeda*) as well as red pine.

The least resistant eastern species are firs (*Abies spp*.), cedars (*Thuja spp*. and *Juniper spp*.), aspens, spruces, birches, sugar maple (*Acer saccharum*), and scarlet oak (*Quercus coccinea*).

Among western species, the redwood (*Sequoia sempervirens*) is extremely resistant to fire, as is the Western larch (*Larix occidentalis*). Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziessii*) are also highly resistant. All have very thick bark and deep roots. The redwood and larch have high crowns, while the ponderosa and larch grow in open, or relatively open, stands.

At the other extreme, Alpine fir (*Abies lasiocarpa*) has very thin bark, grows in dense stands and is highly susceptible. Only slightly more resistant are western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), Engelmann spruce (*Picea engelmanii*), and Sitka spruce (*Picea sitchensis*), due to relatively thin bark and dense growths.

However, it appears that for all the abundance of past experience of wildland fires it is extremely difficult, if not impossible, to make many meaningful statements about the over-all impact on a national scale of the ecological effects which might result from mass fires resulting from thermonuclear attack. Some reasonably plausible estimates of ecological effects in many local areas can be made, but the problem on a national scale is simply too complex to allow for any but the most general and well-qualified statements in the present state of knowledge. To be more specific: while it is not possible, at the present time, to assess the economic effects in terms of dollar costs, one can say that it is improbable that ecological aftereffects of fire would be a major consideration in comparison with other disutilities.

The long-term ecological recovery of fire or otherwise denuded forest ecosystems would be determined to a large degree by the effectiveness of postattack reforestation and other conservation and flood control operations. Even without such efforts for control, natural succession of plants would presumably proceed qualitatively in most areas, as it has in the past, after large forest fires. There are, however, certain significant differences, mostly having to do with the greater scale of damage resulting from a (large) nuclear war. Repopulation and reseeding begin, as a rule, at the periphery of a devastated area. As Wolfenbarger has pointed out,[85] small organisms tend to disperse from a point in a random fashion which results (after a finite time τ) in an exponential variation of density with distance, i.e.

$$d \sim d_o \, e^{-kx},$$

where d_o is the initial density, x the distance and k a constant characteristic of the disseminule, the weather, etc.

This conclusion is an empirical one, which holds equally for motile and wind-blown species, based on counting sample catches of disseminules at various distances from the origin and plotting the data on semilog paper as a straight line.* If we accept it as given we can calculate the density which will be found at the center of a circular area of radius R (initially empty) after a given time τ, assuming every point outside the circle acts a source of dispersal in all directions. The result, obtained by a simple integration is simply

$$d(\tau) \cong d_o \cdot \frac{2\Pi}{k^2} (1 + kR)e^{-kR}$$

As a first approximation, the total time for repopulation would be inversely proportional to the density after a fixed time, i.e.

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*This may explain why Odum and others have referred to the form of the resultant curve as "logarithmic."[86]

$$T = \tau \left(\frac{d_o}{d}\right) \cong . \ \tau . \left(\frac{k^2}{2\pi}\right) \frac{e^{kR}}{1 + kR}$$

This is not quite correct, because after becoming established at new locations, the repopulating species can begin the dispersal process over again from a new set of sources. Instead of being a linearly increasing function of time, d will, in fact, increase faster. Nevertheless d (τ) is certainly a rough measure of over-all recovery time T. The important consequence of the relation deduced above is that recovery time T at the center of the circle increases *exponentially* (for large R) as the radius R of the denuded area increases *linearly*.

If the above model were an accurate description of the kind of damage to be expected from a nuclear attack, the implications would be very stark indeed. The model fails, of course, if refugia are left inside the hypothetical circle of destruction from which repopulation and reseeding can begin. In reality, one strongly expects the latter to happen. For one thing, fires tend to burn at very different speeds, at different times, in different directions, and on different kinds of terrain. (Recall the difference between speed of advance uphill versus downhill, discussed in the last section.) Moreover, wind directions can and do change, so that it is quite usual for a large fire to leave many unburnt islands in a sea of ashes. Ignitions themselves tend to be distributed freakishly because of variations of local topography, wind and weather conditions. The propensity of fallout for coming down unevenly, after leaving intensely radioactive "hot spots" and clear areas in close juxtaposition, is one of the most salient lessons of our experience with atmospheric testing of nuclear weapons.

However, one must admit that beyond noting the existence of these irritating (to the analyst), but fortunate, departures from theoretical uniformity and regularity, the phenomenon has not received nearly as much attention as its potential importance would seem to warrant. As far as biological recovery is concerned, the deviations and fluctuations are central and it would be helpful to know more about their occurrence and distribution. The one case where refugia would *not* be expected to remain undamaged would be following a true firestorm. In this case the scaling law just enunciated is quite likely to be approximately valid, and therefore large firestorms--if they should occur--may well be the worst of all effects of nuclear war on the environment.* As will be pointed out in the next section, if biological recovery is long delayed the land may be so damaged by erosion that restoration can never be more than partial and incomplete.

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*For reasons just outlined, we emphatically disagree with fire experts who have argued that the consequences of "firestorms" and conflagrations would be essentially indistinguishable. The significant distinction, of course, is not thermo-dynamic but biological. On the other hand, we find no reason to dispute the statement by other fire experts that firestorms are extremely unlikely to occur in large sizes in wildlands--that, if they occur at all, they will be local phenomena.

7. Erosion, Floods and Silting

The fundamental cause of erosion is removal of the protective plant cover from watersheds. Proximate causes of this removal may be plowing, harvesting, overgrazing, logging, road-building, mining, fire, drought, disease, or attack by insects or rodents. Farming, grazing, strip mining and indiscriminate logging have been the chief offenders in the past; the first two are the most likely culprits for the future, since logging is now carried out, for the most part, by corporations with a vested interest in preserving the productivity of the timber-growing areas, while strip mining is coming under increasing control and scrutiny by public agencies.

The potential erosion hazard resulting from a nuclear attack may be analyzed in part by examining the various ways in which the above-mentioned human activities may be checked or stepped up as a result of the conditions obtaining in a postattack situation. We may conjecture that all of the causes mentioned may be somewhat exaggerated to the extent that more attention is likely to be focused on immediate problems of production than on long-term conservation measures. Insofar as this is true, it would seem that farming and the grazing of livestock are the most likely to increase in intensity and cause trouble.

As we shall argue elsewhere, food prices in general are quite likely to go up as a consequence of decreased per-acre productivity generally and a sharply increased emphasis on relatively inefficient meat and milk production in particular--because these foods involve the least danger of Sr-90 contamination. Hence it would not be surprising, for example, if there were some tendency to permit overgrazing of marginal lands in areas of low rainfall such as the eastern slopes of the Rockies.* This, in turn, could result in more frequent outbreaks of grasshoppers or Mormon crickets (see section 3 of this chapter), causing a further catastrophic depletion of the ground cover. It is well known that this kind of cycle can get out of control, as has happened in much of North Africa, Greece and the Middle East--once fertile areas--where uninhibited grazing by goats and sheep effectively prevent reforestation of denuded hillsides.[87]

Apart from continuing human activity, of course, plant cover may be damaged by other factors attributable to the effects of the use of nuclear weapons. In this connection we have already discussed radiation, fires (primary and secondary), and outbreaks of pests. It remains to examine the specific mechanisms leading to erosion <u>per se</u>: falling water (rain), flowing water, and wind, and the damage which may be done as a result.

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*It may be important to distinguish between the lower slopes and foothills, and the upper slopes of the mountains, where grass does not grow well and grazing is not a problem. In the Western U.S., 85% of the water used for irrigation comes from runoff from the higher slopes where pine, spruce and aspen are found, yet only 10% of the silt accumulated in reservoirs comes from these elevations. On the lower foothills (piñon-juniper) the principal cause of erosion seems to be overgrazing by livestock, which reduces the ground covering of the grasses.

The initial effect of rain is splash erosion. The total kinetic energy of raindrops falling on an acre of ground at the rate of 2 inches/hour has been described as being sufficient to

> "Lift the 7-inch topsoil layer to a height of 3 feet 86 times during an hour's rain, equivalent to 518 million foot-pounds of work."[88]

This may be a thousandfold or more larger, for a given volume of water, than the kinetic energy of the thin sheets of surface runoff water resulting from the same size storm. Actual erosion rates vary for different soil types. Fine sand is the most readily detachable, while clay or fine-textured soils resist detachment better because of a tendency to aggregate into lumps. On slopes, the splashed soil moves both up and down: the per cent moving downhill is roughly given by 50 plus the per cent of slope and, of course, the soil particles going downhill move farther on the average than particles moving uphill.[89]

Compaction and surface waterproofing of bare soil due to the pounding of rain occurs quickly, typically within a few minutes, and as much as 95-98% of the total storm water may run off on the surface instead of soaking into the ground.[90] In so doing, it carries away many of the detached soil particles. Smooth laminar flow on the surface occurs at first, but as the moving sheet of water increases in depth, turbulence sets in, enhanced by continual splashing of raindrops. Subsequently, channeling takes place, accompanied by increased water velocities, greater turbulence and scour-erosion, whereby the energy of small moving particles is transferred by collisions to cause larger particles to start to move.

As a general rule, erosion and runoff are more severe on burned tracts. One set of figures for Oklahoma showed increases by multiples of 12 to 31;[91] another set for the pine forests of the Sierras showed runoff up by a factor of from 31 to 463 and erosion up by factors of 2 to 239.[92] Results naturally vary with topography, soil and type of vegetation.

The rate of flow of a stream of moving water confined to a particular channel is proportional to the cross-sectional area times the integrated mean velocity. A model which probably fits actual behavior with reasonable accuracy might assume that a given change in rate of flow f can be assigned equally to changes in depth, width and velocity, for a given channel slope and resistance to flow. Thus, the scaling rules for cross-sectional area A and velocity v in terms of flow f would be:

$$A \sim f^{2/3}$$

$$v \sim f^{1/3}$$

Kinetic energy associated with the stream flow would scale as Av^2, or

$$K.E. \sim f^{4/3} \sim v^4$$

FIGURE 4.5

97

FREQUENCY VS. SEVERITY OF FLOODS
(SUSQUEHANNA RIVER AT HARRISBURG)

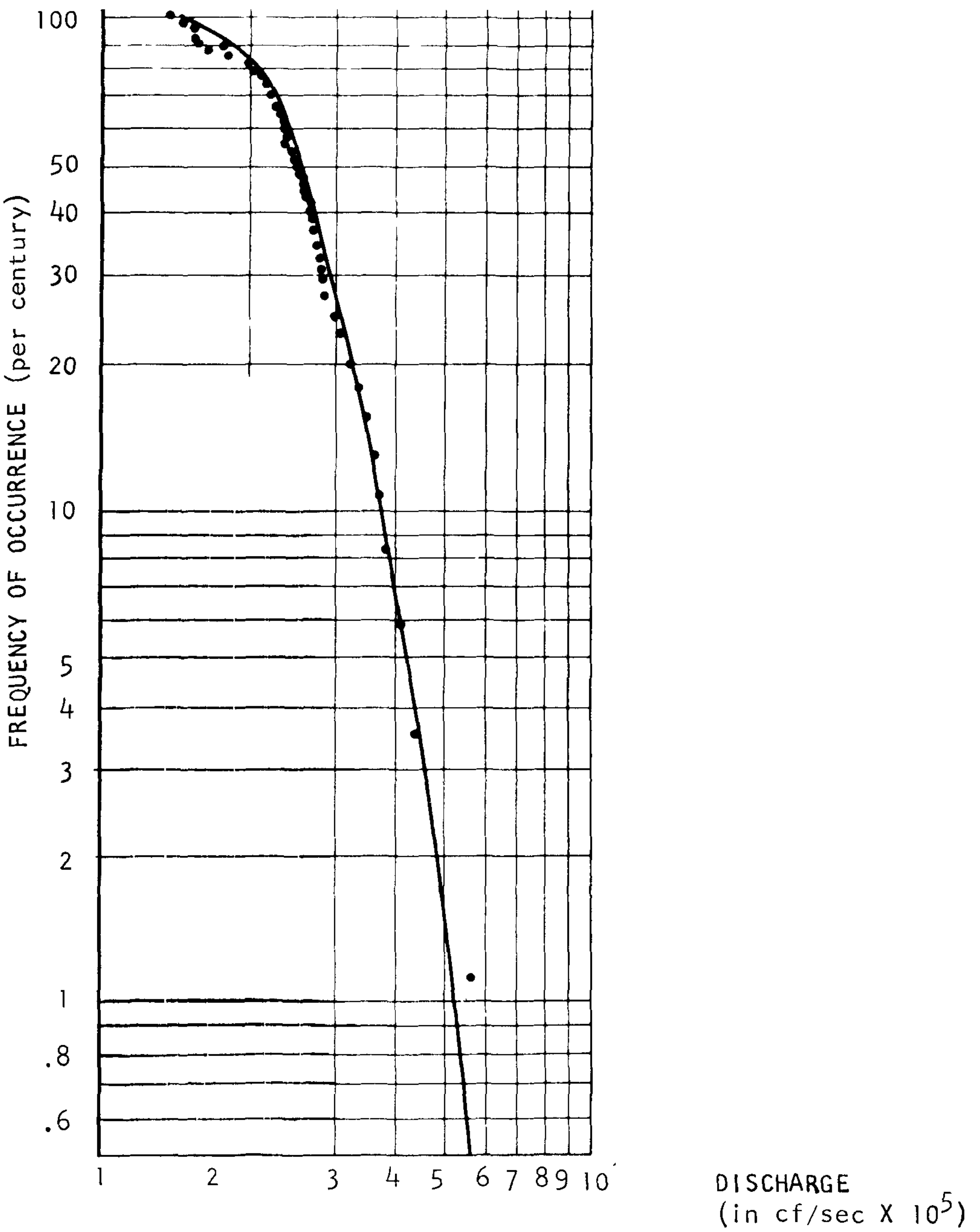
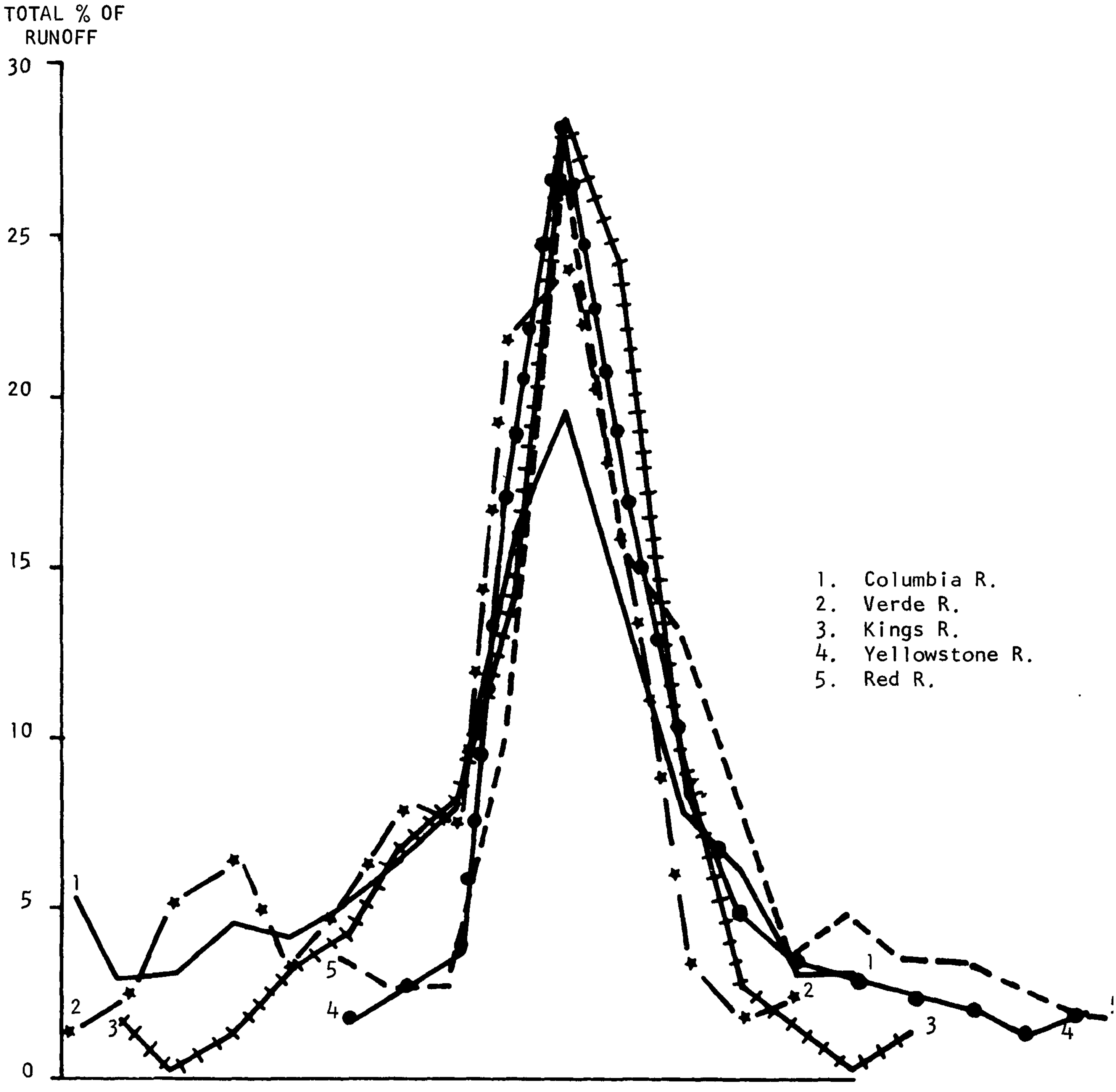


FIGURE 4.6

SEASONAL VARIATIONS OF
ANNUAL RUNOFF FROM FIVE SNOWFED WESTERN RIVERS
SHOWN WITH MONTHS OF PEAK FLOW SUPERIMPOSED[98]



PEAK MONTHS: MAY-JUNE IN NORTH
FEB.-MARCH IN SOUTH

incidentally, that the likelihood of other more permeable types of frost increases the more humus there is in the soil, the more litter above it, and the denser the vegetation. Mature hardwood forests are the least susceptible to concrete frost; bare fields and burned patches are the most susceptible.[99]

The surface vegetation also has an effect on snow accumulation and the rate of melting. The Wagon-Wheel Gap experiment in Colorado has attempted to measure the effect quantitatively: two neighboring watersheds were carefully compared for eight years while in a virgin state, then the timber was cut on one of them and observations were continued for an additional seven years. In the absence of forest cover average streamflow from snow melt increased 16% while peak streamflow increased 50%. Erosion also increased, although damage in the experimental area was small because local soils happen to be very porous allowing rapid penetration.[100]

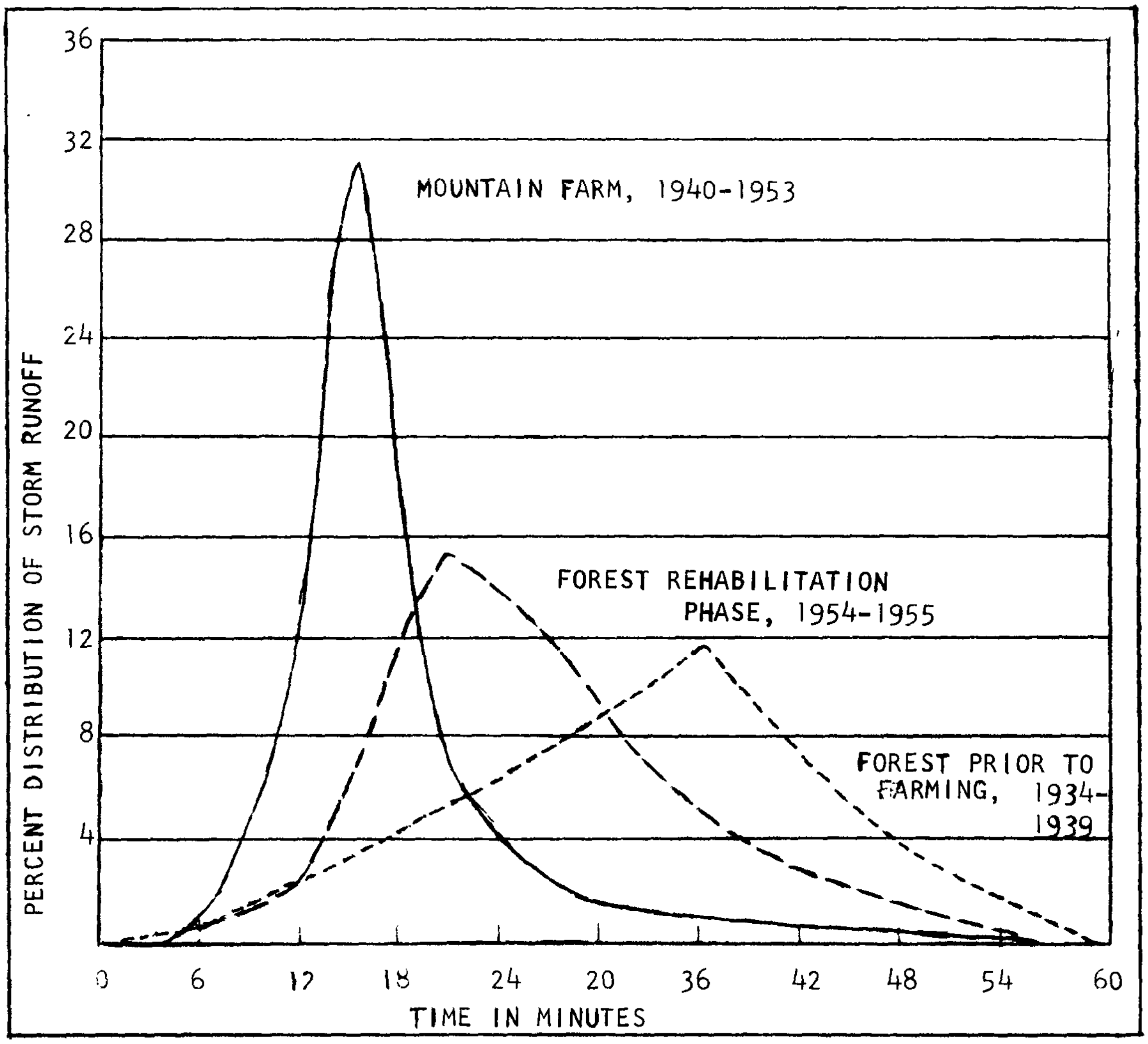
In relatively small headwater streams the conditions for a maximal flood are, more likely than not, simply a very heavy local thunderstorm. Although individual upstream floods are less dramatic than the occasional downstream floods, the Soil Conservation Service has estimated that upstream floods account for more than half of total damages. Here the effect of vegetation is more direct: vegetation intercepts raindrops and traps some water which is re-evaporated before even reaching the ground. Moreover, by dissipating the force of the falling water, soil compaction and "water-proofing" are prevented, whence more water actually penetrates. Finally, it offers resistance to surface runoff by clogging channels with organic litter. Sheet and scour erosion are prevented because running water never attains a great enough velocity.

The effect of direct interception and trapping of water by vegetation is limited due to saturation. Once all the foliage and litter are thoroughly wet, additional rainfall must either soak into the ground or run off on the surface. Eventually the soil itself may become saturated, which means any further water income must be matched by outflow. However, the damage done by the water depends on rate, rather than volume of flow. As has been noted previously, "scouring capability" varies as something like the 4/3 power of stream flow (in cubic feet/sec.) and as the 4th power of velocity.

That the rate of runoff depends intimately on the condition of the watershed and, in particular, the plant cover, is shown graphically by Figure 4.7, which illustrates some results of measurements taken over a period of years at the Coweeta Hydrologic Laboratory, Ashville, North Carolina. This compares rates of runoff as normalized for equal volumes of water actually measured at the weirs. The difference in maximum rates, in the case shown, between the mountain farm and the untouched forested hillside amounts to a factor of 2.5. However, a more significant comparison would show up if we could plot actual runoff for equal amounts of water deposited on the watershed by the storm. Where vegetative cover is severely depleted, as was pointed out earlier, up to 98% of the total rainfall runs off on the surface once the bare soil surface is compacted and sealed by pounding raindrops. This occurs in only a few minutes. In

FIGURE 4.7

DISTRIBUTION OF SUMMER STORM RUNOFF FOR VARIOUS CONDITIONS[101]



the case of a thickly forested hillside, on the other hand, practically all of the water is intercepted by foliage and eventually soaks into the ground, reaching the streams indirectly and gradually. Thus, in comparing equivalent storms, it is not inconceivable that the peak flow of runoff could vary by a factor of 10 or more from one case to the other.

Taking this into account, the over-all runoff rate for the "mountain farm" can be enormously greater than for virgin hillsides. In the particular case illustrated, the "before and after" difference was a factor of 8 (800%).

There is, therefore, little doubt that upstream damage, i.e. erosion in foothills and watersheds,* would increase drastically if plant cover should be depleted directly or indirectly as a result of nuclear attack. By analogy (noting the similarity of the curves in Figure 4.6 with those of Figure 4.7, despite the different time scales) it might be argued that downstream damage would increase correspondingly due to the operation of the same mechanisms. That is, it might seem reasonable to expect the curves, under conditions of accelerated erosion, to have higher but narrower peaks and to carry more runoff water (because less water soaks into the ground). Should this occur, it is obvious that channel capacity could be very greatly exceeded at peak runoff and that little water would flow at other times, resulting in calamitous spring floods and water shortages during the rest of the year. However, the above argument is flawed. It is true that the peak flow and the rate of buildup and decline are related: the faster the buildup, the higher the peak, for a given amount of water. However in a small upstream watershed the rate of buildup of the streamflow is directly related to the rate of percolation of water through the vegetation, and into and through the soil. The type and density of vegetation is of paramount importance. On the other hand, downstream the rate of buildup and decline--which, for a given volume of water alone determines the peak flow--depends mainly on details of topography and weather and only slightly on vegetation or its absence. The one plausible mechanism for large downstream floods is simply the likelihood of an increased total volume of water from the upstream tributaries, due, perhaps, to greater snowmelt runoff (as in the Wagon Wheel Gap experiment) or to the prevalence of "concrete" frost under defoliated or burned-over areas.

One would not, therefore, expect increases in peak downstream flow by factors of 5 or even 2. On the other hand an average of 10-20% more runoff is not at all inconceivable. If the slow watershed recovery period should coincide in a year with the appropriate meteorological conditions for extreme flood conditions, an unprecedented flood disaster might easily occur,** since a 20% increase in maximum streamflow would probably result in a far greater percentage increase in maximum damage.

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*"Upstream" and "downstream" are normally divided operationally as being above or below major existing or proposed flood control structures such as dams.

**In this we differ with H. H. Mitchell,[102] who argues, mainly from the saturation phenomenon without considering any of the other points, that downstream peak flow would not be appreciably increased by destruction of ground cover.

Table 4-6

Losses Due to Erosion and Flooding*

Damage due to erosion, sedimentation and floods may be classified roughly as indicated below:[104]

	Upstream Damage (millions)		Downstream Damage (millions)	
Erosion		$ 750		--
Sedimentation		132		$ 28
Flood Total: (excl.sediment)				
Agriculture	$392		$165	
Misc. Property	153		335	
		545		500
		$1427		$528

Total Actual Annual Damage:	$1955
Total Potential Annual Damage:	$2338

Upstream damage and erosion (above flood control projects) is divided geographically as follows:

"Old South" (9 states)	29%	
Northern Great Plains (Missouri River basin)	20%	
North Central Upper (Mississippi River basin)	19%	
Southwest (4 states)	18%	
Pacific Drainage Area (5 states)	5%	
		91%
All the rest		9%
		100%

Downstream damage is concentrated on a relatively few rivers:

Mississippi Basin:			
Lower Stem (below St. Louis)	24 %		
Upper Main Stem (above St. Louis)	13 %		
Ohio River	12.3%		
Missouri River	6.9%		
Other tributaries (Red R., White R., Ark. R.)	5.7%		
		61.9%	
California (Sacramento, San Joaquin, Klamath)		11.7%	
Atlantic Coast		11.1%	
Columbia-Snake		7.4%	
			92.1%
All the rest			7.9%
			100.0%

---

*These figures are more than three times as high as figures compiled by White and quoted by Mitchell.[103] We prefer our figures for three reasons: (1) they are more recent (1955 vs. 1945 and 1939), (2) they come from official (USDA) publications and (3) it is likely that the earlier compilations omitted certain categories of damage which the latter ones included.

Agricultural damage (as the term is used in the above table) refers to damage to growing or stored crops resulting primarily from standing or moving water, and sediment. Erosion damage results as fertile soil is removed from its productive location; sedimentation damage occurs when fertile valley soils are covered up or diluted by accretions of sterile subsoil. Altogether, some four billion tons of soil are transported each year by water in the U.S. of which 25% reaches the oceans; the rest is deposited in stream beds and alluvial plains mainly by floods.[105]

The indirect economic damage done by accelerated erosion and consequent flooding is probably greater than the above accounting suggests. For one thing, large sums of money are spent on various flood control measures such as dikes, dams, levees, dredges, etc. These are not permanent improvements to the landscape, for they would be unnecessary if constant upstream erosion were not taking place and, because of silting which raises the levels of river beds in the lower valleys, they must be increased year by year as long as erosion continues. By the same token, the amount of land under threat of flooding increases as the level of the river beds rises. If we include both upstream and downstream areas, about 5% of the land in the United States (95,000,000 acres) is estimated to be potentially floodable.[106] This figure tends to increase gradually with time as stream beds rise due to erosion and sedimentation which has already occurred.

The average annual savings in terms of annual damage not done because of existing flood control measures--entirely (by definition) in downstream areas--is estimated by the U.S. Army Corps of Engineers to be $383 million (i.e. $911 million potential damage less $528 million actual damage) which means that downstream areas are currently about 42% protected. Savings of potential erosion damage due to existing soil conservation measures have not been estimated quantitatively as far as we know.

Destruction of plant cover as a consequence of nuclear attack, whether by radiation, fire, insect attacks or by overgrazing* due to altered patterns of agriculture, would also enhance wind erosion. It is clear, for example, that forest trees act as windbreakers as well as soil and water retainers. The importance of this for the microclimate near the ground was discussed previously (section 4 of this chapter). Even a modest reduction of ambient wind velocities near the soil surface has a marked effect. A study in Schleswig-Holstein in north Germany showed that hedgerows between cultivated fields, by reducing air circulation, reduced evaporation from the soil surface to an extent equivalent to a 33% increase in annual rainfall.[108] Of course, dehydration tends to prevent the cohesion of soil particles into clumps and reduces them effectively to powder. Physical barriers also inhibit wind erosion in another way by trapping the heavier particles and preventing the abrasive action which would otherwise occur as the particles accelerate. From 60% to 95% of the moving soil mass never

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*Careful long-term experiments at the Coweeta Hydrologic Laboratory, Asheville, No. Carolina, have demonstrated the consequences of heavy grazing, logging and mountain-farming on steep slopes in terms of erosion.[107] Overgrazing produced by far the worst effects, although serious erosion did not occur for several years. In the first few years surface litter prevented rapid runoff; not until channel blockages of organic detritus had been washed away did erosion become rapid.

rises more than one foot above the surface. Most of the material moves by a process known as "saltation," which consists of short sliding or rolling movements along the surface, followed by bounces of jumps through the air. The heaviest grains "creep" as a result of impacts from particles in saltation. The ratios of distance traveled to maximum rise of these forward jumps range from 7 to 10, with the larger ratio for jumps over six inches in height. Thus the width and depth of furrows are important. The overall rates of movement of eroding material increase with distance downwind from a barrier to a maximum which is determined by drag forces. For completely erodable soils (e.g. fine dune sand) maximum velocity is reached in 10 yards, but for most cultivated soil maximum would not be reached for 500 yards or more. Hence the efficacy of even rather widely spaced barriers such as hedges.[109]

The eroding capabilities of unchecked wind were well illustrated by the dust bowl of the 1930's which resulted from an almost complete loss of ground cover due to overcultivation and low rainfall. Fortunately the situation was (at least temporarily) alleviated by several years of good rains and some improvements in agricultural practice.

In summary, there are a number of ways in which a nuclear attack on the United States might cause, directly or indirectly, depletion of plant cover. The probability of one or another of these mechanisms operating, as a function of enemy targeting, megatonnage, active-passive defense, etc etc., is discussed in other chapters. Our concern in this chapter has been with the later consequences of loss of plant cover, particularly erosion and flooding.

Of course erosion and floods, like fire, are not mortal problems. Their consequences can only be discussed in economic terms. However, the long-term potential disutility of these consequences ought to be taken very seriously. An atomic war in the 20th century might conceivably be remembered in the 22nd century, chiefly because of damage done to the landscape--much of which would still be visible to people living then.

This risk is not due to any special eroding capabilities of nuclear weapons, but simply due to the fact that erosion and flooding are serious menaces to the future economic health of the nation which are not under control at the present time. The most optimistic view is that the situation is getting worse at a slower rate than it was a generation ago. At present rates of degradation, the land and soil resources of the United States will be dangerously strained within a century. Worse, such tenuous defenses against erosion as have been constructed to date have essentially no margin for safety. In other words, the situation is not yet stabilized. It might be compared to a forest fire whose breakneck pace has been laboriously slowed down--but which still burns and still advances. A shift in the wind could still bring disaster. Because of the lack of margin, a nuclear attack appears likely to play such a role (i.e. as a shift in the wind), triggering a new cycle of destruction which would be harder than ever to control. The quantitative questions (how much?, how expensive?, how long?) are too difficult to attempt to answer on the basis of existing data and such few theories as have been devised to date.

8. Balance of Nature

Several of the topics already discussed--most especially insect/pest outbreaks (section 3 of this chapter)--are relevant to the so-called balance of nature. However, it is worthwhile looking at the question again in the following terms:

Nature is commonly, and generally correctly, perceived to be a complex system with a vast number of components whose mutual interactions act as a set of checks and balances on each other. Is it possible, or likely, that if this balance is seriously disturbed the whole arrangement may readjust itself in a new configuration which is (incidentally) less favorable to man?

At first glance this proposition appears to be (1) perfectly plausible, and (2) exceptionally difficult--if not impossible--to test either experimentally or against theoretical knowledge of acceptable universality. However, not to be so easily daunted, let us examine the implications of the proposition, and then look at the arguments which have been, or might be, used on both sides of the question. This, at least, is a reasonable intellectual exercise, and it may prove to be unexpectedly revealing.

The proposition (in its affirmative form) implies that the "balance" of nature is both delicate and unstable, i.e. it is easily upset. The kind of metaphors which are most often cited to make this position seem plausible are typified by the following:

1. Only a few slow neutrons are sufficient to start a chain reaction in an atomic pile (or bomb) releasing enormous energy.

2. A few photons can trigger a laser in the same way with analogous results.

3. A few micrograms of vitamin B-12 can make the difference between life and death for an organism.

4. "For want of a nail the shoe was lost; for want of the shoe the horse was lost...."

5. If the average temperature on earth were a few degrees (on the galactic scale) hotter or colder, life as we know it could not exist....

On the negative side, it seems almost unnecessary to point out that the various analogies or metaphors are all only marginally relevant, at best, to the actual question. Essentially they all illustrate cases where an entire ordered structure--or an important event--depends on a crucial key element or trigger, and attention is entirely focused on this key element. To revert to the atomic bomb as an example: unless all the right steps are taken in exactly the right order, nothing drastic happens. An unarmed bomb can be dropped, melted, exposed to intense radiation or vibration, immersed in salt water or boiling acid, etc., without any serious consequence.

As regards the "balance of nature," then, one must ask first, whether there exists any comparable "trigger"--and second, whether the effects of a nuclear attack would be tantamount to pulling the trigger. Much of this study is, in a sense, devoted to looking to see whether such a potentially unbalancing sequence of events can be identified. Whether due to lack of imagination or insufficient objectivity, or for some other reason, the fact remains that neither the author nor anybody else (so far as he is aware) has succeeded in finding a likely example.

In spite of this negative evidence, the abstract possibility still remains open. Granting that mechanical analogs are somewhat unsatisfactory, it may be helpful to look back into history to see if there are any examples, perhaps on a smaller scale, of ecological upsets which ultimately resulted in stabilization in some radically different pattern.

For purposes of analysis it is convenient to consider (1) consequences (if any) of events of great magnitude which occurred suddenly, and (2) changes which occurred slowly, as a result of continuous pressures over a long period of time. Some promising classes of examples include the

(1) Sudden Catastrophes

Earthquakes & tsunamis
Volcanic eruptions
Meteorites
Storms
Fires
Freezes
Floods

(2) Gradual Changes

Glaciation
Systematic agriculture and exploitation of natural resources; population "explosion"
Establishment of new species (mutation or importation)
Chemical polution

Since an exhaustive analysis is impossible, we must restrict ourselves to picking some of the more dramatic instances of each type.

a. Sudden Catastrophes

Appendix E contains information about a number of cataclysmic natural events which have occurred suddenly. We shall omit discussion of the details here because, although some catastrophes involved extensive destruction of vegetation--notably volcanoes and fires--in no known case has there been any significant long-term imbalance of the "chain reaction" type. Ecological succession following fires has already been dealt with (section 6 of this chapter). Succession following volcanic eruptions seems to be qualitatively similar, except to the extent that soil fertility may be increased or decreased. The particular case of Krakatoa has been studied in detail by Ingersoll.[110]

Some simplistic comparisons may be helpful at this stage. Clearly one (though not the only) salient measure of the "size" of a disturbance is the amount of energy dissipated in the process. A convenient unit is the megaton.[*] The following table exhibits some relevant magnitudes. (Methods of calculation are described in Appendix E.)

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[*] One megaton is equivalent to 10^{15} calories or 4.186×10^{22} ergs.

Table 4-7

Magnitudes of Historical Disasters

Event	Date	Estimated Energy in MT's	Uncertainty Factor[*]
Vredefort meteorite (S. Africa)	prehistoric	2,500,000	>10
Ries Kessel meteorite (Germany)	prehistoric	500,000	>10
Tomboro volcano	1815	112,000	3
Coseguina volcano	1835	44,000	3
Krakatoa volcano	1883	20,000	3
Wei-Ho earthquake	1556	6,500	3
Lisbon earthquake	1775	3,500	3
Chile earthquake	1960	1,500	3
Tunguska meteorite	1908	700	±50%
Forest fire, Paraná, Brazil[111]	1963	360	±50%
Forest fire, Peshtigo, Wisc.	1871	300	±50%
Eastern seaboard hurricane (e.g., "Carla")-instantaneous kinetic energy only[**]	1961	170	±25%
Arizona meteorite	prehistoric	36	>10

Some of the events on the list were not only larger, but very much larger in terms of energy, than any nuclear war which can presently be envisioned. Probably the greatest convulsion in recent history was the Tomboro eruption of 1815. Some world-wide meteorological effects--i.e. "the year without a summer"--have been attributed to this (see Chapter III), but nobody to the author's knowledge has associated any characteristic ecological consequences with vulcanism.

Admittedly such comparisons are interesting and perhaps mildly suggestive, but hardly conclusive. Most of the energy of the major catastrophes mentioned was kinetic energy, dissipated ultimately in the form of heat, which reached the biosphere slowly or not at all. The "coupling coefficient" with biological systems, for most of these cases, is relatively small, especially beyond the immediate area of destruction. The various forest fires, it may be noted, produced far more biological damage over greater areas than earthquakes or volcanoes but involved far smaller energies.

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[*] Most of the numbers are fairly uncertain, but by no means equally so. We have mainly given the geometrical mean of the likely limits. Thus, if the given uncertainty factor is 10, the correct figure is presumably somewhere in the range between 10 times larger and 10 times smaller (i.e. 1/10). For uncertainties less than a factor of 2 it is more convenient to express the range in terms of per cent, hence the given number may be thought of as the arithmetical, rather than the geometrical, mean of the limits.

[**] Total energy dissipated would be much larger.

The crucial point is that nuclear weapons effects, especially radioactivity, interact more efficiently with living organisms than energy spent on shaking the earth or moving the atmosphere. From this standpoint it is likely that chemical pollution, which will be discussed subsequently, is a better analog for nuclear attack than massive natural convulsions such as earthquakes, volcanoes or storms.

b. Glaciation

During the glacial epochs a great sheet of ice covered most of northern Europe, Canada, and Russia, accompanied by drastically lower temperatures ($\sim$10°F. on the average), lower world-wide rainfall, and--over a period of several hundred thousand years--major changes in the dominant fauna of the temperate zone. Mastodons, saber-toothed tigers and other forms disappeared and humans emerged. On the other hand, the "supporting cast" of other phyla does not seem to have changed greatly. Most insects, for example, date back much further. The only instability which reveals itself to a superficial retrospective view concerns the identity of the dominant species. Moreover, a major factor in man's triumph seems to have been his lack of morphological specialization--i.e. his adaptability to new circumstances--which is rather more suggestive of a tendency to (biological) stability, or homeostasis, than the reverse.

c. Systematic Agriculture, Etc.

A number or civilizations have risen and fallen as they discovered, used, and used up exploitable resources,[112] mainly agricultural. Without contributing to the argument as to what the causal relations might be, it seems safe to say that these episodes have often resulted in major disturbances to the local balance of nature. The most recent and most important case has been the colonization of North America by the white man. Among other things, this process has involved cutting or burning about a million square miles of forest (some of which has since re-grown), plowing up the Great Plains, elimination of the bison and the Red Indian, damming and contaminating the rivers, starting and preventing fires, and so on.

The physical changes have evidently been immense in magnitude. Furthermore, the stresses imposed by human activity have been highly selective. Livestock, wheat and other useful animals and plants have been deliberately introduced and cultivated on a large scale. Klamath weed, Japanese beetles, gypsy moths, chestnut blight and Dutch Elm disease were brought in inadvertently and did much damage. Bison, coyotes, wolves and other species have been virtually eliminated--intentionally, if not always intelligently. Again, the specialized dominant species has proved least stable.* The changed balance may be equally apparent if one closely examines any other

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*Bison dominated the plains, as chestnut trees dominated the eastern forests. The same instability can be observed among the dominant conifers spruce, pine, fir and hemlock--as witness their susceptibility to insect epidemics, etc.

broad class. For example, pigeons, sparrows and starlings were certainly not part of the bird population of North America before the white man arrived, whereas eagles, owls and hawks were certainly more common. The insect population mix has adjusted similarly to the human presence: cockroaches, houseflies, bedbugs, cotton boll weevils, potato bugs, corn borers, tobacco hornworms and wheat stem sawflies would not have been present in important numbers in a random sample of insects collected three hundred years ago on this continent.

It seems quite clear, however, that if mankind left the scene, the landscape a hundred years hence would be almost indistinguishable to anyone but a specialist from what it was when (white) man first arrived, except that wild cattle would probably dominate the prairies in place of bison, as the chestnut has already given way to the oak and hickory in eastern forests. Otherwise it would be hard to see the difference. The forest would again extend to the Mississippi and grass, to the mountains beyond.* This is not mere conjecture or wishful thinking; every time man relaxes his pressure, the process of reversion begins. The configuration of the ultimate "climax" ecosystem is implicit, like a controlling blueprint even in an early transitional stage. The cyclic transition from cultivated annuals to hardy annuals (weeds), to hardy perennials to shrubs, fast-growing softwood saplings, and finally slow-growing long-lived hardwood giants (even the seeds of which may not have been present in the field when the process began) does not depend much apparently on the particular species represented--although there will be local variations--but on generalized characteristics shared within fairly wide limits by a large number of species.

d. Establishment of New Species

This phenomenon has also been touched on previously. Several examples are listed and discussed in the attached Table 4-8. They are roughly of two sorts. One sort consists of cases where the invader competed directly against--and replaced--an established species, e.g. as the brown rat replaced the black rat, or as Homo sapiens replaced Cro-Magnon man (who had replaced Neanderthal man). It could be said that the new species took over a pre-existing "niche" in the ecosystem without greatly disturbing the occupants of neighboring niches. It is clear that this replacement is a characteristic of evolutionary development and must occur quite frequently.

In other cases it appears new niches had to be created or, in a manner of speaking, unoccupied ones were occupied for the first time. Ripples of successive adjustments and readjustments were felt by species (ecologically) quite remote from the source of the disturbance. Several examples of this, giant snail, water hyacinth, and rabbit have been described in detail by

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*As a point of interest, the mechanism which favors grasses over trees in drier areas is probably fire: woody plants require many more years to get established than grasses. Rigorous and probably ill-advised fire suppression in dry areas of Texas have already created millions of acres of mesquite and chapparal on land which was formerly suited for grazing (section 6).

Table 4-8

Invasions

Species	Origin & Date of First Instroduction	Extent of Greatest Damage	Methods of Control	Comments
Mosquito[113] (*Anopheles gambiae*)	1930-Brazil (native to Tropic Belt of Africa) Probably transported on a French destroyer from Dakar.	N.E. Brazil from Natal to Fortaleza and Jaguaribe River Valley	insecticides (applied inside houses) destruction of larvae in breeding grounds, e.g. fuel oil completely eradicated in its area of introduction	feeds on men & cattle carries malaria. caused severe malaria epidemics, over 20,000 died
Mediterranean Fruit Fly[114] (*Ceratitis capitata*)	1929-Florida-spread over 10,000,000 acres 1956-Florida 1962 (June)-Florida (Mediterranean region)	Hawaii & Florida citrus & deciduous fruits	spraying with insecticides vigilance over shipments of horticultural products Has now been effectively eliminated from the U.S.	never found in wild hosts Thrives best in temperatures of 16-32° C. & relative humidities of 65-75%
Colorado Potato Beetle[115] (*Leptinotarsa decemlineata*)	1824-Eastern slopes of the Rocky Mountains from Canada to Texas 1870-spread across U.S. rate of 85 miles per/year (local-Colorado)	potato crop areas, now world-wide	paris green spraying or dusting foliage with DDT, dieldrin, or thiodan.	feed by chewing leaves & terminal growth
Gypsy Moth[116] (*Porthetria dispar*)	1869-Medford, Mass., from France (native to Europe and Japan)	confined to New England states & small areas in SE Canada	Parasites of the moth (Europe & Asia) Coal-tar creosote over winter-egg masses Spraying trees with DDT, lead-arsenate	Pest of shade trees, both deciduous & evergreen Strips foliage
Japanese Beetle[117] (*Popillia japonica*)	1916-Riverton, N.J. (Japan)	from southern Maine to N. Carolina, westward to W. Va.	cultural control: delayed planting Spraying foliage & fruit with: DDT, Sevin, Methoxyclor. Traps "milky disease" of grubs	More destructive in U.S. than native area (Japan)

Table 4-8

Invasions (Continued)

Species	Origin & Date of First Introduction	Extent of Greatest Damage	Methods of Control	Comments
Cereal Leaf Beetle[118] (*Oulema melanopa*)	1962-Galien, Michigan (Brought from Europe aboard a freighter via the St. Lawrence Seaway)	cereal crops in Michigan, Ohio, & Indiana; expanding rapidly	quarantine spraying with: malathion & sevin	Breeds prolifically Eats anything that grows
Imported Fire Ant[119] (*Solenopsis saevissima richteri*)	1929-Alabama (S. America) 1956-Fort Benning, Ga.	Gulf Coast 300 persons treated	Scatter dust: chlordane, dieldrin Bait of kepone: destroy mounds	Stings can kill birds & mammals in rare cases
European Wild Rabbit[120] (*Oryctolagus cuniculus*)	1788-1859-Scattered locations on coast of Australia & Tasmania 1859-Became critical upon entering Victoria	By 1928 had invaded 2/3 of Australian continent	Deliberate innoculation with Myxomatosis (1950)-- Cross-continental fence	Myxomatosis caused 80-90% mortality at first, but has now become endemic in smaller, partially immune population
Sea Lamprey[121] (*Petromyzon marinus*)	1930-Invaded Lake Erie via Welland 1937-Infested Lake Huron & Lake Michigan 1946-Lake Superior	Lake Michigan--1945-49, 93% decrease in fish catch--destroyed fish industry in all Great Lakes	Discovery and poisoning preferred breeding grounds. Threat ended by 1950.	
Giant African Snail[122] (*Achatina fulica*)	1800-observed in Mauritius (native of East Africa-in particular, Kenya & Zanzibar) 1936-established in Hawaii	SE Asia & the Pacific	(none fully effective) Methods used: 1) Metaldehyde (molluscicide) 2) some predatory beetles 3) giant toads	Spread eastward from E. Africa to Micronesia, India, Ceylon & Hawaii appetite for rotting & decaying matter
Starling[123] (*Sturnus vulgaris*)	1890-New York City (native of Europe) imported deliberately	abundant in East beginning to appear on Pacific Coast	discourage nesting	

Table 4-8

Invasions (Continued)

Species	Origin & Date of First Introduction	Extent of Greatest Damage	Methods of Control	Comments
English Sparrow[124] (*Passer domesticus*)	1850-New York City	greatest abundance in cities where few native birds are found entire U.S.	discourage nesting	Population increased in direct proportion to the degree of environmental modification by man
Brown Rat [125](Norway Rat) (*Rattus norvegquicus*)	1727-entered Russia (native of western China)	spread rapidly over Europe (fully occupied by middle of 18th century) replacing the black rat	Traps Bait protection of natural enemies of rats diminution of the available shelter	Carries disease-bubonic plague and trichinosis
Nutria Rat[126] (*Myocastor*)	1936 (Dec.) Willamette Valley, Oregon	found from Brazil and Argentina to Chile	Traps	People raising nutria for fur, turned the rodents loose when it became nonprofitable. Nutria bred rapidly & now devastating crop fields.
Klamath-weed or goat-weed[127] (*Hypericum perforatum*)	1900-Klamath River, California (native of Europe)	Rangeland-by 1950 invaded 2.5 million acres of rangeland	Import insects *	Unpalatable to stock

* *Chrysolina gemellata* and *C. hyperici* (beetles)

Table 4-8

Invasions (Continued)

Species	Origin & Date of First Introduction	Extent of Greatest Damage	Methods of Control	Comments
Prickly Pear Cactus[128] (*Opuntia inermis*)	1840-imported to Australia (native of U.S.)	grazing land; covered 60 million acres by 1925	Import insect[*]	moth cut infestation in Australia by 95% in 7 years
Dutch Elm Disease[+][129] (fungus-*Ceratostomella ulmi*)	1930-imported to U.S. in elm burl logs (discovered in Netherland 1919)	Northeast U.S. various kinds of elms natural stands of elm shade-tree areas	none adequate	A beetle carries the fungus which causes the disease[‡] Spores introduced into cambium as beetles feed
Chestnut Blight[‡][130] (fungus-*Endothia parasitica*)	1904-first reported in New York City (imported from Asia)	entire U.S. (has killed 100% of American chestnut trees	None effective	beetles carry the fungus

[*] Argentinian moth: *Cactoblastis cactorum*

[+] It is carried by the European Elm Bark Beetle: *Scolytus multistriatus*

[‡] The beetle was imported from Europe in 1904 and was observed in Boston, Mass. The relationship between the beetle and the Dutch Elm Disease was not discovered until 1930.

Ingersoll.[131] In no case we have seen, however, did the chain of successive interspecies interactions result in a more violent adjustment at the end of the chain than at the beginning i.e. the disturbance was not amplified. This is an observation which will occasion little or no surprise among biologists; yet it is just the opposite of what we think of as a chain reaction (re the atomic bomb). In every case we have studied, biological perturbations--or ripples--caused by the appearance of new species are rapidly smoothed out. The altered balance differs from the original mainly in that the identity of the components is slightly changed. The respective roles of the larger functional groups--families, orders and phyla--tend to remain substantially unchanged. The ecosphere is evidently quite stable with respect to this kind of disturbance.

e. Chemical Pollution

Abstractly considered, as remarked previously, ecological imbalances resulting from indiscriminate injection of various toxic chemicals into the environment might be the best available analogs for purposes of potential consequences of nuclear war.

Effects of chemical pesticides on plant and animal communities have been a prime topic of public concern in recent years, especially since the publication (1962) of Rachel Carson's book Silent Spring[132] and subsequent (1963) Hearings before the Senate Committee on Government Operations.[133] Numerous case histories have been cited, but among the most dramatic are the large-scale spraying episodes summarized in Table 4-9.

Probably the most notable thing about the cited programs--especially in the fire ant "eradication" campaign--was that despite the comparatively huge quantities of poison used, the insect targets were not in fact eradicated: two years later all the pests in question were back in large numbers. (Large-scale spraying projects have been largely discontinued since 1959, due to the inconsiderable benefits, and considerable ancillary damage, which they produced.) However, the insecticides in question decay very slowly, if at all (the analogy with Sr-90 or Cs-137 is curiously apt), and continue to be present in sublethal quantities in pond waters, soil organisms, earthworms, grubs and so forth. There is continuing stress on certain species of animals higher in the food chain, e.g. birds and fish, which seem to accumulate unusual quantities of the chemicals in their bodies, particularly the fatty tissue around the liver. In addition to verified direct bird and fish mortality above 90% in some cases,[134] the breeding rates of some species of birds, e.g. woodcock, Bobwhite quail and wild turkeys, dropped drastically. Since the sprayed area is a winter breeding ground for woodcock (among others) from the whole of North America, the ecological effects are not restricted to the locality where the poison was used.

One apparent result of the program to eliminate the fire ant was a startling increase in pests of sugar cane, although the ecological mechanism is obscure.[135] Although this, as well as the other side effects mentioned above, was presumably temporary, the most notable long-term consequence of continued chemical spraying is probably the disruption of natural

Table 4-9

Large-Scale Spraying

Date & Place	Poison	Quantity lbs/acre	Extent (acres)	Target	Consequences
1955	DDT	~.8	300,000	Spruce budworm (Montana, Wyoming)	Large loss of freshwater fish
1957	DDT	1	2,950,000	Gypsy moth (N.Y., N.J.)	Bees killed, fruit crop damaged, birds & fish killed
1958-59	Dieldrin Heptachlor	2-3	20,000,000	Fire ant (Alabama, et al.)	Very high mortality among birds (esp. game) wildlife, cattle, poultry, etc. Fire ants not significantly reduced 2 years later

Most synthetic insecticides are quite toxic to most forms of animal life, viz.

Chemical	Approx. lethal dose
DDT	.25 mg/gm. (body wt.)
Heptachlor	.025 mg/gm. (body wt.)
Dieldrin	.004 mg/gm. (body wt.)

biological controls on pest species--particularly in the case of the gypsy moth--coupled with an increasing immunity to the chemicals themselves.[136]

Another notable example of chemical pollution of the environment occurred as a result of the use of various lethal gases such as chlorine, phosgene, diphenylchlorarsine and diphenylcyanarsine in World War I. The areas involved in gas attacks were sometimes fairly extensive, e.g. 50 square miles. There was also a disastrous explosion at the German depot on Lüneberg Heath which resulted in considerable contamination of the surrounding area.[137]

Damage to plants in the above instances was relatively temporary. There was some defoliation of trees, for example, but roots were not affected and regrowth followed.

A study of the potential environmental hazards associated with chemical weapons concluded that in the absence of experimental evidence, expected damage would be analogous to that from a fire.[138] One important difference is noted: whereas reseeding is often favored by fires which consume underbrush and litter, leaving a mineral bed, this would not necessarily be true, for example, of forests destroyed by chemicals.* Reseeding might be delayed until standing snags decayed and fell, providing good seedbeds for species such as spruce (see section 6 of this chapter).

Ecological consequences of pollution caused by industrial wastes have also been studied extensively.[139] "Smog," the irritating brew of hydrocarbons, sulfur dioxide, and atmospheric oxygen and nitrogen, created in the atmosphere by the photochemical action of the sun's rays, is known to damage plants and other animals as well as humans. (The decline of the California citrus industry is, in part, due to the effects of Los Angeles smog.) The prime example of this kind of pollution is probably the so-called Tennessee Copper Basin (of which carbon copies can be found in Montana and elsewhere), where sulfur-containing fumes from copper smelting have killed off all vegetation and inhibited regrowth in nearby areas for a number of decades. As a result the land has eroded so badly that reforestation is now extremely difficult and expensive, if not impossible. Ingersoll has discussed the Tennessee case in considerable detail.[140] Ecological consequences beyond the area of direct damage, however, appear to be minimal.

Chemical wastes injected into streams by sewage disposal plants, chemical plants, paper mills and other industrial activities have detrimentally affected marine life. The presence of large quantities of chemical wastes tends to cause de-oxygenation, whence aerobic forms of life cannot survive. From progress made in isolated cases, however, it seems clear that once the cause of the problem is eliminated the streams tend to revert quickly to normal.

We are forced to the conclusion that even relatively subtle and insidious disturbances to the environment, created by the presence of

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*Or by radiation, disease or insects.

substantial quantities of a variety of toxic chemical substances which are not present in "nature," are seldom, if ever, responsible for permanent alterations in its balance. In fact, once the environmental irritant or insult is removed, the original balance of nature (or one virtually indistinguishable from it) tends to be quickly restored unless the physical substrate has meanwhile been severely damaged as was the case in the Tennessee Copper Basin.

It has been suggested recently, however,[141] that widespread industrialization and combustion of fossil fuels (and, possibly the effects of a nuclear war) may be permanently altering the composition of the atmosphere in an unfavorable way. The balance between free oxygen and CO_2 is normally determined by the metabolic processes of green plants, which utilize carbon dioxide, and animals, which consume oxygen. If plant growth is inhibited on a global scale, e.g., by widespread chemical or radiological pollution or by alteration of the energy balance of the earth (Chapter III and Appendix C), the ultimate result could be a reduction in the amount of free oxygen in the atmosphere. Combustion processes further reduce the available oxygen supply. It is possible that such a perturbation would be self-compensating if a change in the CO_2 level should stimulate more rapid plant growth. It is not unlikely that, in the absence of contrary influences, such a homeostatic mechanism actually exists. However, there are other factors affecting the rate of plant growth which could conceivably modify the operation of such a mechanism. For example, a decrease in world-wide average temperature could conceivably reduce the over-all rate of plant growth and the associated rate of free oxygen production.*

This discussion would be incomplete without some mention of the importance of the concept of "approach to stable equilibrium," or <u>homeostasis</u>, in biology. The notion has appeared and reappeared throughout this volume, and particularly in the present section. A statement of the principle of equilibriation for biology goes back at least to Herbert Spencer (1864), although its reincarnations were always somewhat vaguely worded and unsuited for predictive purposes until Lotka's careful analysis of conditions and scope of validity.[142]

As Lotka essentially showed, it is difficult to state a biological equilibrium principle which is invariably correct without being ambiguous, or rigorous in the sense of being derivable from first principles, without at the same time being tautological: saying, in effect, "A stable equilibrium is a stable equilibrium." However, many biologists have recognized that in a broader, less trivial formulation, such a principle is <u>statistically</u> valid, i.e., that a deviation from equilibrium almost invariably gives rise to a chain of cause and effect which tends to counteract the change, as an attack by microbes stimulates antibody production. This

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*The complexity of the problem is illustrated by the fact that, if this happened, the CO_2 level would presumably rise and warm up the atmosphere via the "Greenhouse Effect."

phenomenon might be termed quasi-stability. Closer analysis reveals, moreover, that the rare exceptions to this rule (vicious cycles) often have an evolutionary function. Thus, a tiny percentage of spontaneous mutations prove to have useful survival characteristics, although the vast majority are deleterious and fail to reproduce or propagate. In fact, the observed (quasi) stability of biological systems (e.g., species) may well be the obverse aspect of the "law of natural selection"--which eliminates the unfit and, as a corollary, preserves the well-adapted.

The connection between stability and evolution has been emphasized by W. Ross Ashby, who points out that "what survives in a vigorous world must be homeostatic in its reactions; and the ability to behave homeostatically enormously increases a system's chance of survival."[143]

The same author has also emphasized the relationship between homeostasis, as a generalized characteristic of complex systems and the modern theory of communication developed by Shannon and Weaver.[144] The transmission of a signal, obscured by "noise," through a communication channel is homologous to the concept of a self-regulating system in the presence of perturbing external influences. In the former cases, of course, the signal is highly structured and all-important, whereas in the latter cases the "signal" is simply a constant value of some parameter (e.g. body temperature in an organism or relative abundance in an ecosystem). Nonetheless, the ability of a self-regulating system to compensate for perturbations is formally equivalent to the capacity of a channel to transmit a signal through noise.[145] Ashby believes that in highly complex systems such as the brain, the digital computer, and presumably the biosphere, there will exist "all sorts of complex stabilities" and that these may be of more interest than the "degenerate" stabilities of simple mechanisms.

The gist of the last several paragraphs has been that the general applicability in biology of the concept of homeostasis is generally accepted today, whether the basis for it is taken to be thermodynamics, mechanics, statistical communications theory, or natural selection. Thus to the specific case histories which we have actually examined, can be added, in some sense, the whole literature of biology.

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APPENDIX A

DETERMINATION OF Q_R

The calculation of Q_R involves several subtleties: firstly, radiological damage cannot, even approximately, be classified in a binary system (all or nothing), but there is a "gray" region in which damage is a function of dose; secondly, because the effects of fallout are persistent and cumulative so that overlapping of fallout patterns from adjacent groundburst may produce radiation fields whose consequences are not a simple sum of the consequences of either one separately. When multiple overlaps are considered, the problem becomes very complex.

Let us make the following simplifying but not unrealistic assumption that damage to a biome caused by H + 24 hour doses below some dose L is proportional to the dose. Any 24-hour exposure above L is assumed to be "overkill." The portion of total γ activity which contributes to overkill beyond L or to "underkill" below L is essentially wasted. We shall tentatively consider two cases:

$$L = 500 \text{ R}, \qquad L = 1000 \text{ R}.$$

Since the contributions from overlapping patterns are crucial, it would be misleading to try to estimate Q_R from discrete fallout patterns. The use of a log-normal distribution function to approximate the probability of a given point receiving a given dose X has been justified by Everett and Pugh in the case of many weapons of equal size dropped at random into a large area,[1] i.e.:

$$P(X)\,dX = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2}\left(\ln\frac{X}{X_o}\right)^2\right]\frac{dX}{X}$$

where σ and X_o depend on the weight of the attack D, expressed in KT/mi^2 (fission). These parameters were fitted by comparing the theoretical log-normal distribution with distributions for several large attacks, calculated by RAND Corporation, using an early fallout model.* The Everett-Pugh analysis yielded:

$$\sigma^2 = \ln\left(1 + \frac{3.54}{D}\right)$$

$$\ln X_o = 1.95 + \ln D - \frac{1}{2}\sigma^2.$$

where D is the density of fission products, measured in KT/mi^2.

Our verbal definition of Q_R is equivalent to

$$Q_R = \frac{\text{total } \gamma\text{-activity}}{\text{"effective" } \gamma\text{-activity}},$$

---

*It would probably be useful to repeat the procedure for other attack patterns and other, more sophisticated fallout models such as the Miller-OCD model.

where

$$\text{total } \gamma \text{ activity} = \lambda \int_{0}^{\infty} X\ P(X)dX = \lambda X_o e^{\frac{1}{2}\sigma^2}$$

$$\text{effective } \gamma\text{-activity} = \lambda \left[\int_{0}^{L} \frac{X}{L}\, X\ P(X)dX + \int_{L}^{\infty} \frac{L}{X}\, X\ P(X)dX \right],$$

where λ is an unspecified constant of proportionality (which cancels out in the result). On evaluating the integrals and simplifying the resulting expression, one obtains:

$$Q_R = \left[\frac{D}{L}\left(1 + \frac{3.54}{D}\right) e^{1.95} \int_{\infty}^{C-1} e^{-\xi^2}\, d\xi + \frac{L}{D}\, e^{-1.95} \int_{C}^{\infty} e^{-\xi^2}\, d\xi\right]^{-1}$$

where

$$C = \frac{1}{\sigma\sqrt{2}} \ln \frac{L}{X_o} .$$

Figure 1.3 in the text (Chapter I) shows Q_R plotted numerically over a range of values D, both for L = 1000 and for L = 500. We would claim that these approximations are probably good for most plausible attacks on point targets whose initial locations depended in any important way on accident or on long complicated causal chains involving chance factors such as might determine the location of a city.* On the other hand, a deliberate optimization might reduce the Q_R values for small attacks against areas. It will be noted that the lowest values of Q_R for high values of D, are in the neighborhood of 2, which implies that even a random pattern of bursts can result in a fairly efficient overlapping. The potential room for decreasing Q_R for large attacks by exploding the weapons in some sort of regular "checkerboard" or grid pattern is clearly much less than a factor of 2 (25% might be a reasonable guess).

In the case of small attacks, considerable improvement in Q_R could be achieved by bunching the bursts close together, but of course this would localize the damage. It is very hard to imagine an enemy using 1000 MT's, for example, just to attack the state of Kansas.

It should be realized that the calculated Q_R is sensitive to the area covered by fallout up to a certain radiation intensity. Fallout models differ considerably as regards their predictions in this regard (see Section 1, Chapter I). Hence one major uncertainty is still difficult to assess; it would not be surprising if other models led to curves deviating substantially (perhaps by factors of 2) mainly at the low end, from the examples given in Figure 1.3.

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*Topographical features, for example, are distributed in a kind of random fashion.

To adjust crudely for the revised values of the conversion factor $\frac{\text{R/hr at 1 hr}}{\text{KT/mi}^2}$, currently taken to be 3700, it is roughly correct to multiply all doses given by Everett and Pugh by a factor of 3. Recall the discussion in Section 1, Chapter I. To adjust from a 24-hour cumulative dose to a 30-day cumulative dose, assuming immediate entry into the field, a further multiplicative factor of about 6/5 may be assumed.[2] Thus a 1000 R (24-hour dose) is translated to 3600 R (30-day dose) for comparison with our system.

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APPENDIX B

MODEL FOR THE OPTICAL TRANSMISSIVITY OF A POLYDISPERSE DUSTY STRATOSPHERE, AS A FUNCTION OF TIME AND WAVE LENGTH

R.U. Ayres and I.J. Zucker*

The conceptual problem for which a model is needed is the following: at some initial time, t_o, a layer of dust particles with a known distribution of sizes is injected (by means which need not be discussed here) into the isothermal** stratosphere. As time goes on the particles drift slowly down at different rates, depending on size, as governed (on the average) by the Stokes-Cunningham law, until they reach the tropopause where they are quickly "scavenged" out by wind and rain. Hence the particle-size distribution adjusts itself with time in two ways: (1) the over-all density decreases and (2) the relative numbers of larger particles is depleted. The optical transmissivity for a given wave length depends, in turn, on the changing distribution.

The key assumption in the model is that at the starting point, $t = t_o$, the density of particles in the dusty layer is everywhere constant between the tropopause (altitude h_1) and the stratopause (altitude h_2) and that the particle-size distribution is independent of altitude h. Mathematically this can be expressed as follows:

$$\eta(r,h,t=t_o) = \eta_o\,(r)\,\Theta\,(h) \qquad (1)$$

where $\eta_o\,(r)$ is a known function of particle radius r and $\Theta(h)$ is a "step-function" of altitude

$$\Theta(h)\begin{cases} = 0 & o < h < h_1 \\ = (h_2-h_1)^{-1} & h_1 \le h \le h_2 \\ = 0 & h_2 < h \end{cases} \qquad (2)$$

The time evolution of the distribution is assumed to be absolutely (rather than statistically) determined by the Stokes-Cunningham equation[1]

$$v(r,h) = \frac{2}{9}\,\frac{gd}{\mu}\,r^2\left(1 + \frac{A}{rp(h)}\right) \qquad (3)$$

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**Other assumptions about the thermal structure of the stratosphere are frequently made, but the analysis merely becomes more complicated without becoming appreciably more illuminating.

In this expression v is the drift velocity, g the gravitational constant, d the density of particulate material, μ is the viscosity of the medium, p(h) the barometric pressure, and A is an empirical constant.

Numerically, g is an absolute constant, equal to 981 cm/sec^2; the density d can be taken to be about 2.3 gm/cm^3, μ is normally a function of temperature,[2]

$$\mu = 1.5038 \times 10^{-5} \frac{T^{3/2}}{T + 124} \text{ gm cm}^{-1} \text{ sec}^{-1} \tag{4}$$

where T is given in ^{o}C. However, assuming the stratosphere layer in question is isothermal, at a temperature of -55^{o} C, which is a reasonable approximation, one finds

$$\mu = 1.416 \times 10^{-4} \text{ gm cm}^{-1} \text{ sec}^{-1}$$

and

$$A = 4.632 \times 10^{-3}$$

when p is measured in millimeters of mercury and r is in centimeters. The case of non-isothermal layers introduces further complexities which we shall not explore here. The barometric pressure is, of course, a function of altitude (h). Assuming the ICAO* "standard" atmosphere, the tropopause (h_1) is at 36 kilofeet and the stratopause (h_2) is at about 80 kilofeet. In this region (36-80 kilofeet) the pressure as a function of altitude is very closely approximated by an exponential function

$$p(h) = 165 \exp\left[-0.047(h-h_1)\right] \text{ mm of Hg} \tag{5}$$

where p is in mm of Hg and h and h_1 are in kilofeet.

The process of downward drift of the upper boundary and subsequent removal of particles can be represented mathematically as follows, allowing for the fact that the rate of movement differs for each class (i.e., size) of particles. Thus

(6)

where

$$\Theta(h,r,t) \begin{cases} = 0 & o < h < h_1 \\ = (h_2-h_1)^{-1} & h_1 < h < h_2 - u(r,t) \\ = 0 & h_2 - u(r,t) < h \end{cases} \tag{7}$$

The distance u(r,t) must now be determined from (3) and (5). The Stokes-Cunningham equation can be thought of as an equation for the

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*International Civil Aviation Organization.

velocity of the boundary, as described above, i.e., substituting appropriate numbers

$$v(r,h) = \frac{du(r)}{dt} = \frac{2}{9}\frac{gd}{\mu} r^2 \left[1 + \frac{0.28}{r} \times 10^{-4} \exp[0.047(D-u)]\right] \tag{8}$$

where u is in cm. and t in sec. This can be integrated in straightforward fashion to obtain u(r,t)

$$\int_0^{u(t,r)} \left[1 + \frac{0.28}{r} \times 10^{-4} \exp[0.047(D-u)]\right]^{-1} du$$

$$= -\frac{1}{0.047} \ln \left[\frac{1 + \frac{0.28}{r} \times 10^{-4} \exp(0.047D)}{\exp(+0.047u) + \frac{0.28}{r} \times 10^{-4} \exp(0.047D)}\right]$$

$$= \frac{2}{9}\frac{gd}{\mu} r^2 t \tag{9}$$

whence

$$u(r,t) = \frac{1}{0.047} \ln \left\{ \left(1 + \frac{0.28}{r} \times 10^{-4} \exp(0.047D)\right) \exp\left[0.047\left(\frac{2}{9}\frac{gd}{\mu}\right) r^2 t\right] - \frac{0.28}{r} \times 10^{-4} \exp(0.047D)\right\} \tag{10}$$

where t is measured in seconds, r, u(r) in cm. Converting u(r) to kilofeet, t to years, and r to microns one obtains, finally:

$$u(r,t) = \frac{1}{0.047} \ln \left\{\left(1 + \frac{0.28}{r} \exp(0.047D)\right) \exp\left(1.72\ r^2 t\right) - \frac{0.28}{r} \exp(0.047D)\right\} \tag{11}$$

Clearly u(r,t) must not exceed the thickness D of the dusty layer (e.g., 46 kilofeet), which puts constraints on the values of r which are physically allowable after a given time t has elapsed. This condition $[u(r,t) \leq D]$ takes the form

$$\left(1 + \frac{0.28}{r} \exp(0.047D)\right) \exp\left(1.72\ r^2 t\right) - \frac{0.28}{r} \exp(0.047D) \leq \exp(+0.047D) \tag{12}$$

whence

$$t \leq \frac{1}{1.72 r^2} \ln\left(\frac{r + 0.28}{r \exp(-0.047D) + 0.28}\right) \tag{13}$$

where

$$D = h_2 - h_1 \tag{14}$$

This equation describes the rate at which particles with larger radii are depleted from the dusty layer. The results are plotted in Figure B.1. Thus one can read off the curve the largest value of r still represented in the distribution at time t.

Table B-1

REMOVAL TIME FOR PARTICLES OF VARIOUS SIZES

Time t (years)	r cutoff (microns) 40 kilofoot layer	 60 kilofoot layer	 80 kilofoot layer
1	.75	.85	.90
2	.46	.55	.57
3	.36	.40	.42
4	.29	.33	.34
5	.25	.28	.29
6	.22	.25	.26
7	.19	.22	.23

The intensity I of light reaching the lower boundary of the dusty layer is given by

$$I = I_o \exp(-\gamma \, D\sec\psi.) \qquad (15)$$

where I_o is the incident intensity (at the top of the atmosphere), γ is the so called "extinction coefficient," in units of kilofeet^{-1}, and $D\sec\psi$ is the optical path length, in kilofeet, where ψ is the angle of incidence (measured from the normal).

The extinction coefficient γ is defined as the scattering cross section per unit volume:[3]

$$\begin{aligned}\gamma(\lambda,t) &= \pi\rho_o \int_0^\infty dr\, r^2\, Q(r,\lambda) \int_0^\infty dh\, \eta(r,h,t) \\ &= \pi\rho_o \int_0^\infty dr\, r^2\, Q(r,\lambda)\, \eta_o(r) \int_0^\infty dh\, \Theta\,(h,r,t) \qquad (16) \\ &= \pi\rho_o \int_0^{r\ \text{cutoff}} dr\, r^2\, Q(r,\lambda)\, \eta_o(r) \left[1 - \frac{u(r,t)}{D}\right]\end{aligned}$$

where $u(r,t)$ is given by equation 12 and ρ_o is the number density per unit volume of particles (or scattering centers) within the dusty layer. A "unit volume" in this case may be taken as a cylinder one kilofoot in altitude and one micron square (or 10^{-8} cm^2) in cross section. The approximate scattering function $Q(r,\lambda)$ for non-absorbing spheres with an index of refraction m has been derived by Mie[4]

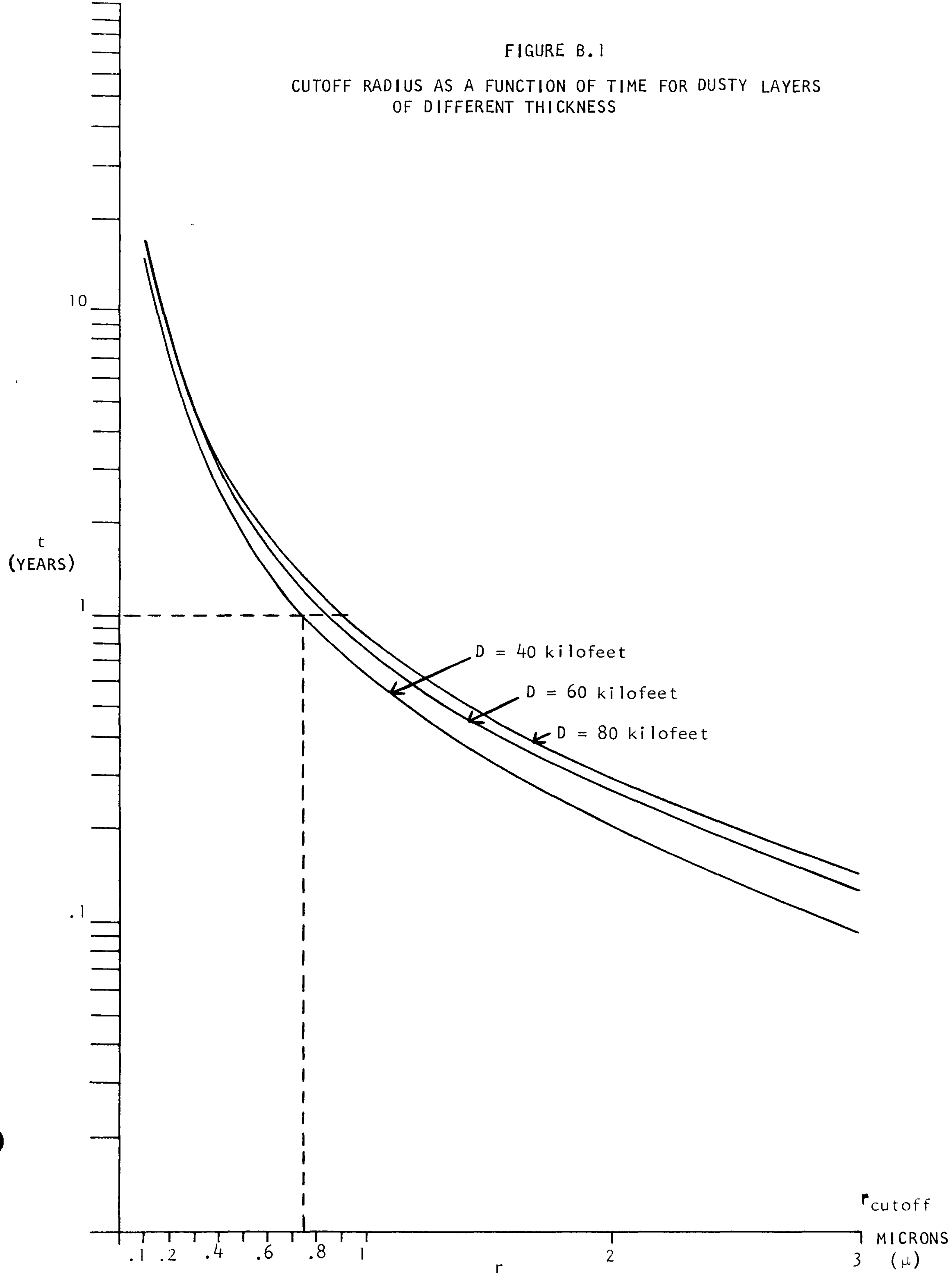
$$Q(r,\lambda) = 2\left[1 + \frac{2}{R^2} - 2\left(\frac{\sin R}{R} + \frac{\cos R}{R^2}\right)\right] \qquad (17)$$

where

$$R = \frac{4\pi}{\lambda}\,(m-1)r \qquad (18)$$

FIGURE B.1

CUTOFF RADIUS AS A FUNCTION OF TIME FOR DUSTY LAYERS OF DIFFERENT THICKNESS



for the case $|m-1| \ll 1$ (although the approximation is quite useful for m as large as 2). It is generally reasonable to assume $m \cong 1.5$, typical of glassy substances. For purposes of this model we shall take $\eta_o(r)$ to be a log-normal distribution function of the form

$$\eta_o(r) = (2\pi)^{-\frac{1}{2}} (\sigma r)^{-1} \exp\left[-\frac{1}{2\sigma^2} (\ln r/r_o)^2\right] \qquad (19)$$

where $\sigma = \ln 2 \cong 0.69$ and $r_o = 1, 2, 5\mu$ respectively. These choices are arbitrary, but are not inconsistent with the discussion of particle-size distribution in Chapter I, Section 1. The calculations for a 46-kilofoot layer have been carried out numerically by one of the authors on a computer at Battersea College of Technology in London. The results for times between 1-5 years are shown at 6-month intervals in Table B-2.

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Table B-2

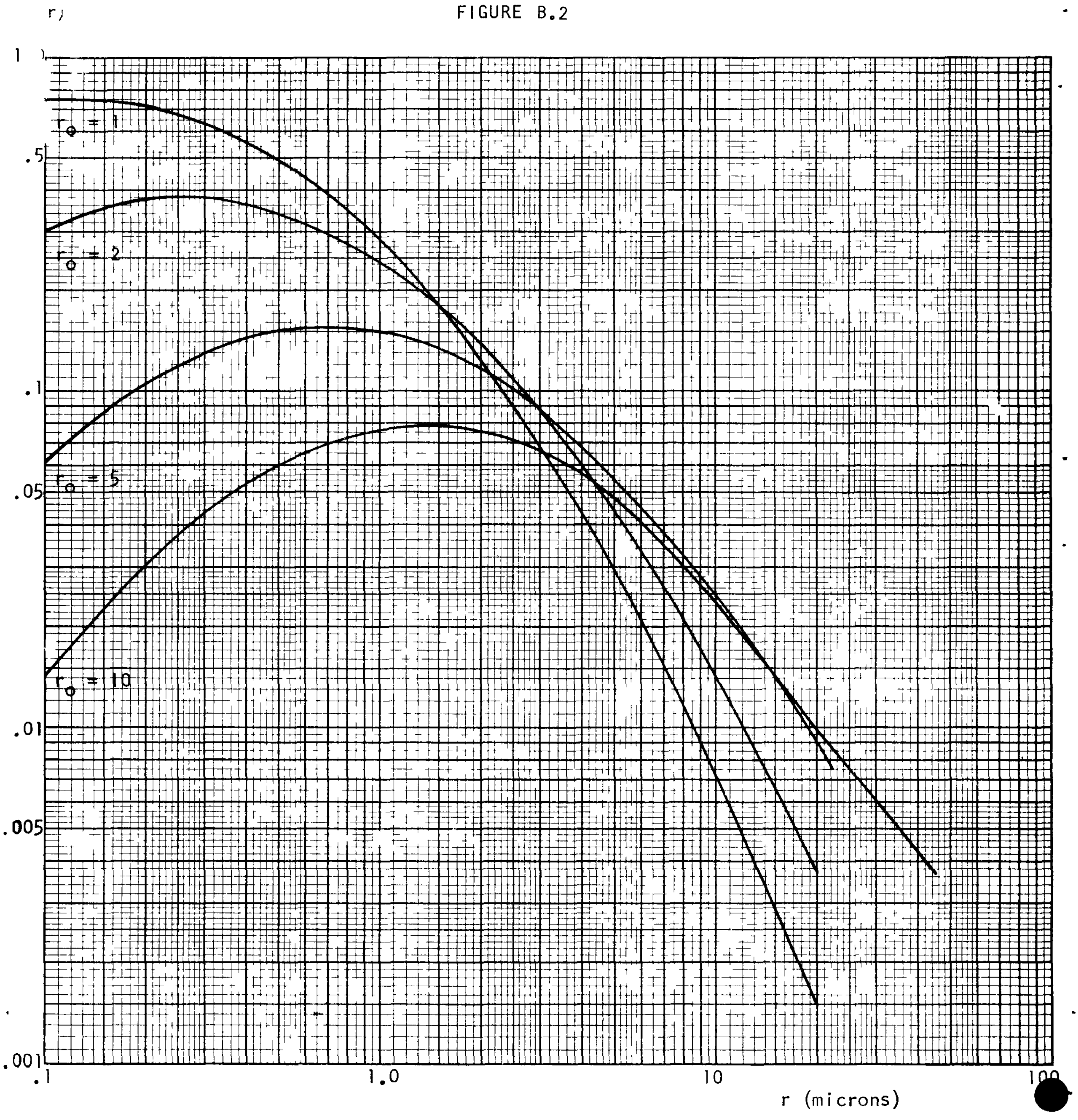
Extinction Coefficient $\gamma(\lambda,t)$

(D = 46 kf)
$r_o = 1.00\mu$

	Time in Years								
λ	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
0.1	0.1438	0.0494	0.0208	0.0099	0.0051	0.0029	0.0017	0.0010	0.0006
0.2	0.1448	0.0500	0.0211	0.0103	0.0052	0.0028	0.0016	0.0011	0.0007
0.3	0.1459	0.0511	0.0208	0.0105	0.0062	0.0038	0.0024	0.0015	0.0009
0.4	0.1497	0.0522	0.0254	0.0136	0.0074	0.0041	0.0023	0.0014	0.0008
0.5	0.1531	0.0625	0.0293	0.0141	0.0071	0.0037	0.0020	0.0011	0.0006
0.6	0.1731	0.0692	0.0292	0.0130	0.0061	0.0030	0.0016	0.0009	0.0005
0.7	0.1922	0.0694	0.0269	0.0113	0.0051	0.0025	0.0013	0.0007	0.0004
0.8	0.2005	0.0655	0.0239	0.0097	0.0043	0.0020	0.0010	0.0006	0.0003
0.9	0.1986	0.0599	0.0209	0.0083	0.0036	0.0017	0.0009	0.0005	0.0002
1.2	0.1650	0.0430	0.0140	0.0053	0.0022	0.0010	0.0005	0.0003	0.0001
1.5	0.1271	0.0308	0.0097	0.0036	0.0015	0.0007	0.0003	0.0002	0.0001
2.0	0.0827	0.0190	0.0058	0.0021	0.0009	0.0004	0.0002	0.0001	0.0001
2.5	0.0566	0.0126	0.0038	0.0014	0.0006	0.0003	0.0001	0.0001	0.0000
3.0	0.0408	0.0090	0.0027	0.0010	0.0004	0.0002	0.0001	0.0000	0.0000

	$r_o = 2.00\mu$					$r_o = 5.00\mu$		
	Time in Years					Time in Years		
λ	1.0	1.5	2.0	2.5	3.0	1.0	1.5	2.0
0.1	0.0341	0.0083	0.0027	0.0011	0.0005	0.0013	0.0002	0.0000
0.2	0.0343	0.0084	0.0027	0.0011	0.0005	0.0013	0.0002	0.0000
0.3	0.0343	0.0086	0.0026	0.0010	0.0005	0.0013	0.0002	0.0000
0.4	0.0352	0.0082	0.0031	0.0014	0.0007	0.0014	0.0002	0.0000
0.5	0.0337	0.0101	0.0038	0.0016	0.0007	0.0012	0.0002	0.0001
0.6	0.0384	0.0117	0.0040	0.0015	0.0006	0.0013	0.0003	0.0001
0.7	0.0447	0.0122	0.0038	0.0013	0.0005	0.0016	0.0003	0.0001
0.8	0.0485	0.0118	0.0034	0.0011	0.0004	0.0018	0.0003	0.0001
0.9	0.0495	0.0110	0.0030	0.0010	0.0004	0.0019	0.0003	0.0001
1.2	0.0432	0.0081	0.0020	0.0006	0.0002	0.0018	0.0002	0.0000
1.5	0.0340	0.0058	0.0014	0.0004	0.0001	0.0014	0.0002	0.0000
2.0	0.0225	0.0036	0.0008	0.0003	0.0001	0.0010	0.0001	0.0000
2.5	0.0155	0.0024	0.0006	0.0002	0.0001	0.0007	0.0001	0.0000
3.0	0.0112	0.0017	0.0004	0.0001	0.0000	0.0005	0.0000	0.0000

FIGURE B.2



LOG-NORMAL DISTRIBUTIONS

$\sigma = 0.69$, $r_o = 1, 2, 5, 10$

APPENDIX C

EFFECTS OF STRATOSPHERIC ATTENUATION ON THE HEAT BALANCE OF THE EARTH'S SURFACE

Table C-I, compiled by Kondrat'yev[1] and reproduced below, indicates the relative importance of various major energy exchange processes affecting the thermal balance of the earth. Taking the estimates of Budyko, Yudin and T.G. Berlyand (in the first column) as a basis for calculation, the situation can be summarized briefly in terms of inputs and outputs.

Table C-I

Average Annual Thermal Balance of Earth

Components of the thermal balance (%)	Ref. 2	3	4	5
Shortwave radiation				
Received at the upper boundary of the atmosphere	100	100	100	100
Reflected from clouds into space	27	25	27	30
Reflected into space by atmospheric scattering	7	9	6	8
Absorbed by clouds	12	10	11	
Absorbed by the atmosphere				15
Solar radiation	6	9		
Radiation reflected by the earth's surface	2		3	
Reaches earth's surface;				
As direct solar radiation	30			30
As diffuse radiation	18			17
Absorbed by the earth's surface;				
Direct solar radiation	27	24	11	27
Diffuse radiation	16	23	34	16
Reflected from earth's surface;				
Direct solar radiation	3			3
Diffuse radiation	2			1
Thermal radiation				
Total thermal radiation of the atmosphere	151			146
Including:				
Radiation into space	55	66*	48	50
Atmospheric emission reaching the earth's surface	96	105		96
Thermal emission of the earth's surface	116	119		120
Including:				
Absorbed by the atmosphere	108			112
Radiation into space	8		17	8
Net radiation of the earth's surface	20	14	23	24
Other components of thermal balance				
Turbulent heat transfer from the earth's surface to atmosphere	4	10		-4
Latent heat of condensation (or evaporation)	19	23		23

*Including thermal radiation from the earth's surface.

Table C-2

Atmosphere

	Short-Wave (SW) Radiation	Long-Wave (LW) Radiation	Other Processes (OP): Convection; Turbulent Transfer; Evaporation; Condensation
Energy Income (units)	100	108	23
Energy Outgo (units)	80	151	0
Net (units)	+20	-43	+23

Table C-3

Surface of the Earth

	SW	LW	OP
Energy Income (units)	48	96	0
Energy Outgo (units)	5	116	23
Net (units)	+43	-20	-23

The balance for the earth-atmosphere-space system as a whole can be deduced from the above, i.e.,

Table C-4

Earth - Space

	SW	LW	OP
Energy Income (units)	100	0	0
Energy Outgo (units)	37	63	0
Net (units)	+63	-63	0

The question now arises: Suppose an incremental change in the earth's reflectivity of optical wave lengths (albedo) is imposed, e.g. by creating a layer of dust in the stratosphere. Net SW income (Table C-3) would then be reduced by some factor $1-e_1$, and the entire system of energy flows would have to adjust itself to maintain a net (LW) outgo equal to the reduced net (SW) income. The various transfer mechanisms would not, presumably, scale exactly in proportion to e_1. Therefore, assume

e_2 = fractional (negative) change in LW emission from atmosphere

e_3 = fractional (negative) change in LW emission from earth's surface

e_4 = fractional (negative or positive) change in other processes, especially evaporation/condensation

The conservation equations expressing the balance of income and outgo for the atmosphere and the earth, separately, are

$$\begin{aligned} 0 &= 20(1-e_1) - 151(1-e_2) + 108(1-e_3) + 23(1-e_4) \\ &= -20e_1 + 151e_2 - 108e_3 - 23e_4 \end{aligned} \tag{1}$$

$$\begin{aligned} 0 &= 43(1-e_1) + 96(1-e_2) - 116(1-e_3) - 23(1-e_4) \\ &= -43e_1 - 96e_2 + 116e_3 + 23e_4 \end{aligned} \tag{2}$$

Summing (1) and (2) gives the conservation equation for the entire system

$$0 = -63e_1 + 55e_2 + 8e_3 \tag{3}$$

We have, in effect, two relations involving three unknown quantities. A third equation involving e_2, e_3 and e_4 would be sufficient to determine all the variables. Such an equation could be obtained, in principle, by expressing all the emission and absorbtion rates as functions of a single parameter, e.g. temperature, and then comparing the magnitudes of the variations of each function. Thermal radiation from the ground is fairly accurately approximated by the "black body" law

$$F = \sigma T_G^4 \tag{4}$$

where T_G is the absolute temperature of the ground. Other heat transfer processes are more complicated, however. For example, the atmosphere is not a "black body," due to selective absorbtion of some infra-red wave lengths by CO_2 and water vapor. The most common version of the empirical Angström equation, describing radiation flux from a clear sky, is equivalent to[6]

$$F = 0.95\,\sigma T_A^4\,[0.194 + 0.236\exp(-0.8W)] + \sigma(T_G^4 - T_A^4) \tag{5}$$

where T_A is the air temperature two meters above the ground surface, and W is the mass of water vapor in the atmosphere in a vertical cylinder of 1 cm^2 cross-section. The latter quantity is implicitly temperature dependent in a complicated way. Actually (5) is unsatisfactory on grounds quite apart from the fact that it does not take into account the influence of clouds.[7] There is no simple but adequate empirical equation available. Much the same can be said of the relations governing convective or turbulent heat transfer and evaporation/condensation phenomena.

In the absence of clearcut empirical (or theoretical) equations we must resort to a rather inelegant heuristic argument. The average equilibrium temperature of the atmosphere is somewhat lower than that of the earth's surface, because (disregarding details) the SW energy income from the sun must be balanced by a net outward flow of heat. This in turn implies a negative average temperature gradient whose magnitude varies smoothly and monotonically with absolute temperature (e.g. of the earth's surface).* Let

$$e_2 = X(e_1)e_3 \tag{6}$$

where X is a proportionality factor which is presumably less than unity. Solving for e_2, e_3 and e_4 one obtains:

$$e_2 = \left(\frac{63X}{8 + 55X}\right) e_1 \tag{7}$$

$$e_3 = \left(\frac{63}{8 + 55X}\right) e_1 \tag{8}$$

$$e_4 = \left(\frac{355X - 327}{8 + 55X}\right) e_1 \tag{9}$$

It can be seen that, if $X(e_1) \leq 0.92$, e_4 becomes negative implying an actual increase in convection and evaporation. This might seem somewhat surprising, at first glance, in view of the fact that convective transfer is essentially proportional to temperature gradient--which one tends to assume would be smaller if over-all radiative heat losses were cut. Evaporation rate is a function of the difference between ambient temperature and the dew point. If ambient temperature is reduced, then evaporation rate must also decrease unless the average humidity declines still faster. But lower average humidity would be associated either with lower average evaporation rate, or with higher precipitation rate (i.e. more rapid turnover of the water vapor in the atmosphere). To the extent that precipitation probability depends on high (rather than low) average humidity--which is certainly one factor involved, though not the only one--increased average evaporation at lower average ambient temperature (i.e. negative e_4) seems contradictory. On the basis of general heuristic arguments, then, it appears likely that $X(e_1)$ will be found in the range:

$$0.92 < X < 1.0 \tag{10}$$

Since both extremes seem to be excluded for physical reasons, it seems reasonable to assume that X tends to avoid them equally, which suggests the value

$$X \cong 0.96 \tag{11}$$

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*This is a very gross approximation. Actually, there are three distinct regions below the ionosphere; (a) up to the tropopause (12-15 km) the gradient is negative, (b) between the tropopause and the stratopause (~ 50 km) it is positive, (c) between the stratopause and the mesopause (~ 80 km) it is negative again. However, 90% of the atmosphere is in the troposphere.

Since the derivation is clearly far from rigorous, there may well be some subtle flaw in the argument. In particular, precipitation may increase due to an increased amount of meridional mixing of air masses, arising from increased N.S. temperature gradients. It would, therefore, be dangerous to rely too strongly on (11).

As regards temperature, above, the exact value of X is not very critical. It is clear from (8) that $e_3 \approx e_1$ provided only that $X \approx 1$, whence

$$e_3 \approx e_1 \cong 4 \frac{\delta T_G}{T_G} \qquad (12)$$

Thus a change of 10% in net SW radiation income (total incident radiation less the fraction immediately scattered or reflected back into space) results in a 2.5% change in average absolute temperature on the ground.

The convection-evaporation picture obviously changes radically with different assumed values of X, as is shown by Figure C.1. A value of $X > 1.11$ results in a ratio $e_4/e_1 > 1$ while a value of $X < 0.92$ results in a negative e_4, as mentioned previously.

The quantum of energy associated with a photon of frequency ν is given by Planck's law:

$$\varepsilon = h\nu \qquad (13)$$

Hence the calculation of e_1 (which is a measure of the change in energy input) is most conveniently carried out if the solar spectrum and the attenuation factor are expressed in terms of frequency ν, rather than wave length λ, e.g. at latitude θ (N. or S.) and rotational phase angle φ measured from the zenith

$$e_1(t,\theta,\varphi) = \cos\theta \cos\varphi \int_0^\infty S(\nu)\ I(\nu,t,\theta)\, d\nu \quad (\mathrm{Cal/cm^2}) \qquad (14)$$

The intensity I, allowing for enhanced scattering by a dusty layer in the stratosphere, is given by

$$I(\nu,t,\theta,\varphi) = I_o \exp[-\gamma(\nu,t)\ D\sec\theta\ \sec\varphi] \qquad (15)$$

where $\gamma(\nu,t)$ is obtained from $\gamma(\lambda,t)$ by substituting the relation

$$\lambda = \frac{c}{\nu} \qquad (16)$$

Since the processes of absorbtion and re-emission of LW radiation, as well as evaporation and convection, have already been taken into account in deriving e_2, e_3 and e_4, it is reasonable to assume the extraterrestrial form of $S(\nu)$, as shown in Figure C.2.[8]

FIGURE C.1

RATIO OF $\frac{e_4}{e_1}$ AS A FUNCTION OF $\frac{e_3}{e_2}$

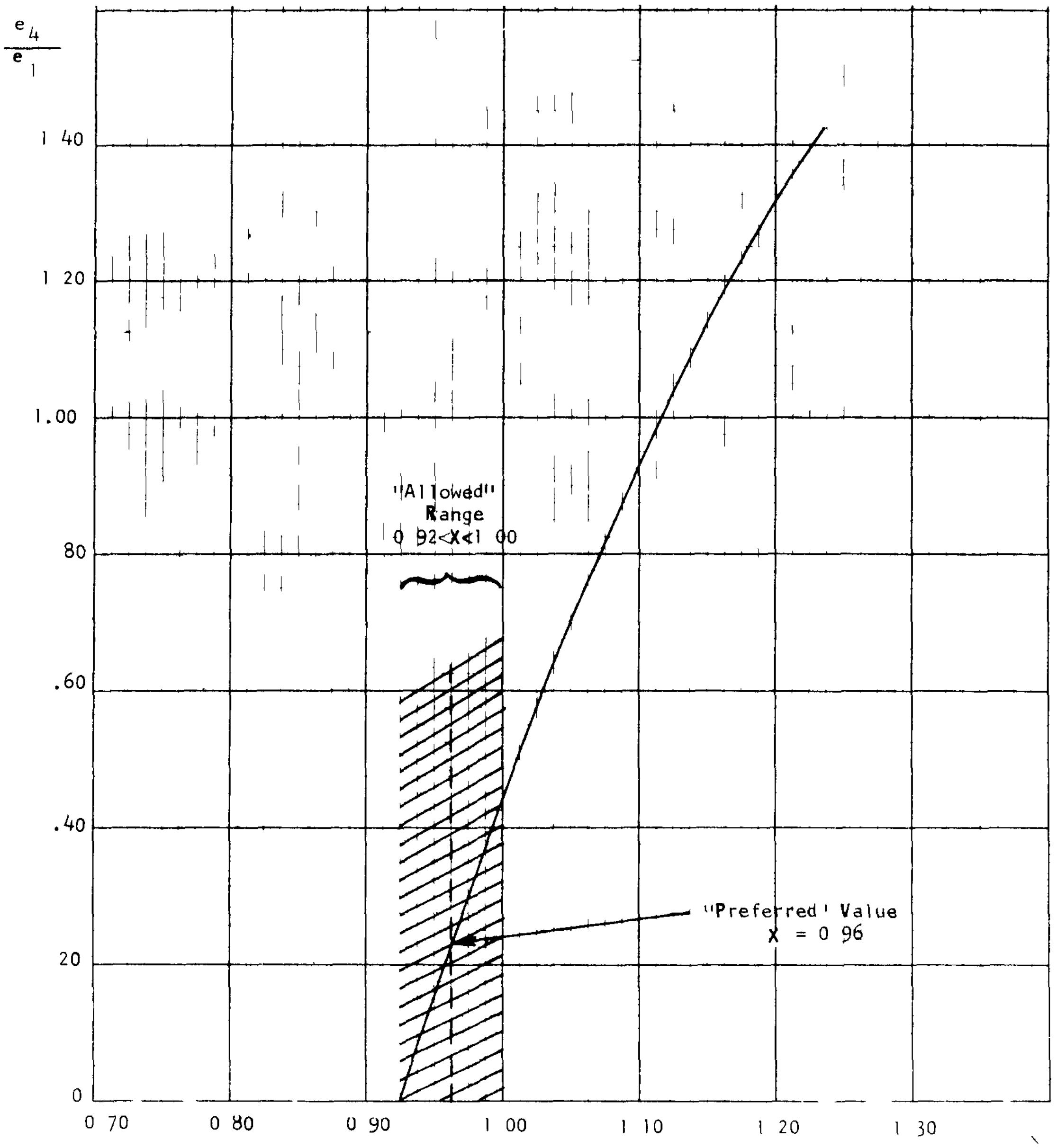
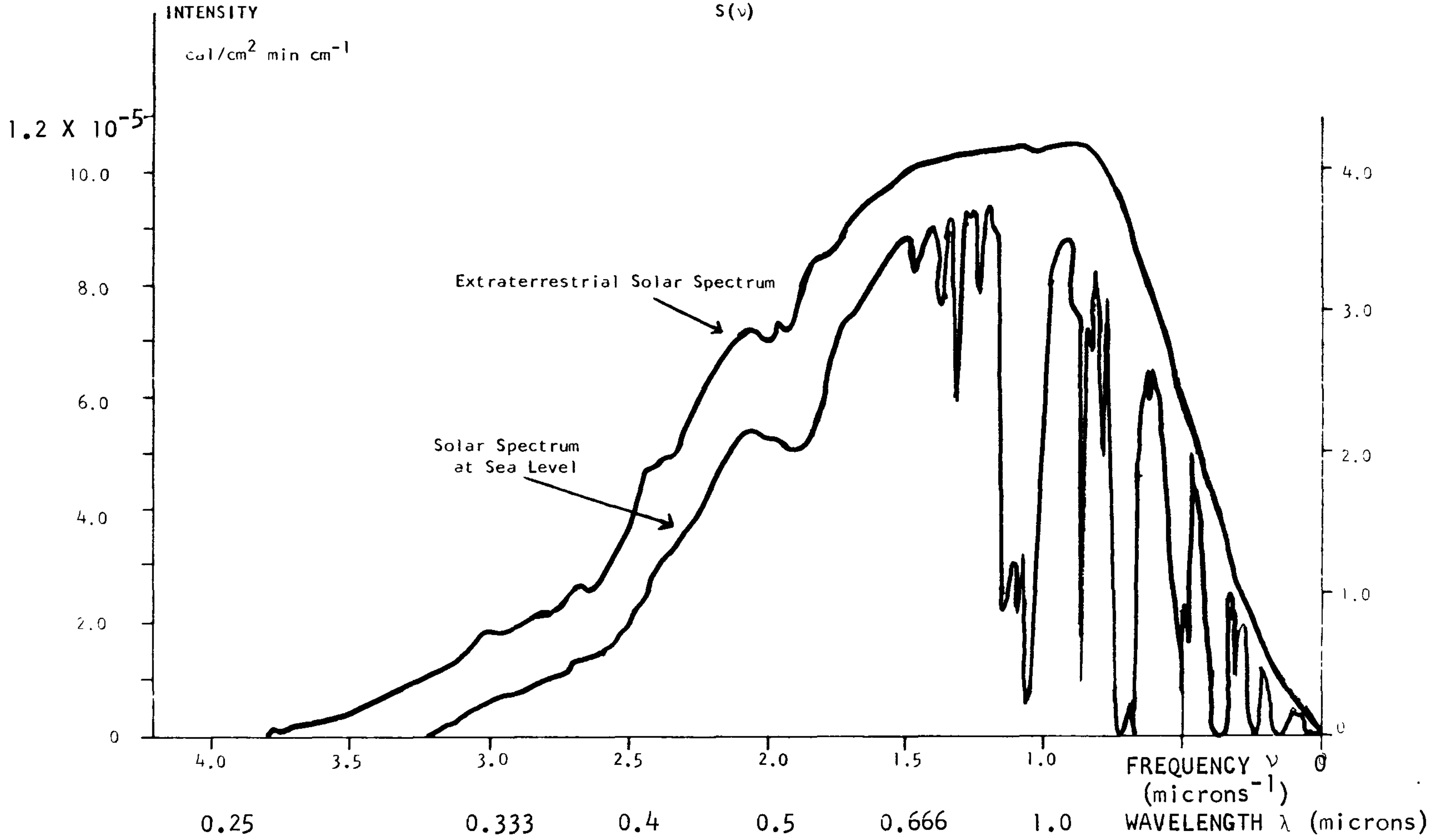


FIGURE C.2

SOLAR SPECTRUM
S(ν)



One should now average over the sunlit hemisphere of the earth, i.e.

$$e_1(t) = I_o \int_0^\infty d\nu S(\nu) \int_0^{\pi/2} d\varphi \cos\varphi \frac{\int_0^{\pi/2} d\theta \cos^2\theta [1-\exp(-\gamma D \sec\theta \sec\varphi)]}{I_o \int_0^\infty d\nu S(\nu) \int_0^{\pi/2} d\varphi \cos\varphi \int_0^{\pi/2} d\theta \cos^2\theta} \tag{17}$$

An exact analytic evaluation of the integrals over θ, φ, is difficult to obtain, and a Taylor series expansion of the integrand in powers of γD diverges. When both θ and φ are near zero we have, to a first approximation

$$1 - \exp(-\gamma D \sec\varphi \sec\theta) \cong \gamma D \sec\varphi \sec\theta \tag{18}$$

provided γD itself is fairly small. However, when either φ or θ, or both, approaches $\pi/2$ one can neglect the exponential, i.e.

$$1 - \exp(-\gamma D \sec\varphi \sec\theta) \cong 1 \tag{19}$$

provided, this time, that γD is not too small. Hence, dividing the φ, θ space into four regions,

$$0 < \varphi < \bar{\varphi}, \quad 0 < \theta < \bar{\theta}$$

$$0 < \varphi < \bar{\varphi}, \quad \bar{\theta} < \theta < \pi/2$$

$$\bar{\varphi} < \varphi < \pi/2, \quad 0 < \theta < \bar{\theta}$$

$$\bar{\varphi} < \varphi < \pi/2, \quad \bar{\theta} < \theta < \pi/2$$

The cross-over points clearly depend on the magnitude of γD.

$$e_1 \cong \frac{4}{\pi} D \frac{\int_0^\infty d\nu S(\nu)\gamma(\nu)}{\int_0^\infty d\nu S(\nu)} \cdot \int_0^{\bar{\varphi}} d\varphi \int_0^{\bar{\theta}} d\theta \cos\theta$$

$$+ \frac{4}{\pi} \left\{ \int_{\bar{\varphi}}^{\pi/2} d\varphi \cos\varphi \int_0^{\pi/2} d\theta \cos\theta + \int_0^{\bar{\varphi}} d\varphi \cos\varphi \int_{\bar{\theta}}^{\pi/2} d\theta \cos\theta \right\}$$

$$= \frac{4}{\pi} \bar{\varphi} \sin\bar{\theta} D \frac{\int_0^\infty d\nu S(\nu)\gamma(\nu)}{\int_0^\infty d\nu S(\nu)} + 1 - \frac{2}{\pi} \bar{\theta} \sin\bar{\varphi} - \frac{2}{\pi} \sin\bar{\varphi} \sin\theta \cos\bar{\theta} \tag{20}$$

It can be verified by inspection that the correction terms in all four regions are negative, which means the above approximation is an upper bound to the true result. Hence, the optimum choices for $\bar{\varphi}$, $\bar{\theta}$ will be such as to minimize the above expression. Setting the appropriate partial derivatives equal to zero in the usual way, one easily obtains the two relations:

$$\cos\bar{\varphi} = \frac{\pi \sin\bar{\theta}}{2(\bar{\theta} + \sin\bar{\theta}\cos\bar{\theta})} M \qquad (21)$$

$$\cos\bar{\theta} = \frac{\pi\bar{\varphi}}{4\sin\bar{\varphi}} M \qquad (22)$$

where it is convenient to introduce the notation:

$$M = D\,\frac{\int_0^\infty d\nu S(\nu)\gamma(\nu)}{\int_0^\infty d\nu S(\nu)} = D\,\frac{\int_0^\infty \frac{d\lambda}{\lambda^2} S(\lambda)\gamma(\lambda)}{\int_0^\infty \frac{d\lambda}{\lambda^2} S(\lambda)} \qquad (23)$$

M being, of course, a dimensionless quantity. These can be solved explicitly once the indicated integrations are carried through (numerically). The solutions of equations (20), (21), (22) for $\bar{\theta}$, $\bar{\varphi}$ and e_1 are shown in Table C-5 and Figure C.4 for a range of values of M.

Table C-5

Values of M, $\bar{\theta}$, $\bar{\varphi}$, $e_1(\bar{\theta},\bar{\varphi},M)$

M :	0.01	0.03	0.1	0.3
$\bar{\theta}$:	1.559	1.535	1.455	1.255
$\bar{\varphi}$:	1.560	1.541	1.473	1.280
$e_1(\bar{\theta},\bar{\varphi},M)$:	0.020	0.059	0.192	0.517

As the results indicate, $\bar{\theta}$ is consistently almost equal to $\bar{\varphi}$ and e_1 is very nearly given by

$$e_1 \cong 2M \qquad (24)$$

except for a slight "tailing-off" for larger values of M (where the approximation begins to be suspect).

The last step is to evaluate M. Values of γ/ρ_o for three cases of interest have already been calculated for various wavelengths (or frequencies) and times (Appendix B). The numerical integration of (23) is straightforward but tedious. Figure C.3 shows $M/\rho_o D$ as a function of time. It remains to fix the parameter $\rho_o D$ in terms of some measurable quantity. Consider a value M = 0.1 at a time t = 1 year. Reading from Figure C.3, it can be seen that this implies

$$\begin{aligned}\rho_o D &\cong .63 \quad \text{in units of microns}^{-2}\\ &\cong 6.3 \times 10^{7} \quad \text{in units of cm}^{-2}.\end{aligned} \tag{25}$$

At time t = 1 year for D = 46 the cutoff radius (Figure B.1, Appendix B) is about 0.75μ, whence the "average" radius will be

$$\hat{r} = \int_0^{0.75} \eta_o(r)\left(1 - \frac{u(r,t=1)}{46}\right) r\, dr \tag{26}$$

and the average volume of the residual particles must be

$$\frac{4\pi}{3}\,\widehat{r^3}(t=1) = \int_0^{0.75} \eta_o(r)\left(1 - \frac{u(r,t=1)}{46}\right) r^3\, dr \tag{27}$$

It is probably reasonable to assume the residual distribution is fairly strongly "peaked," whence close to the cutoff

$$\widehat{r^3} \gtrsim (\widehat{r^2})^{3/2} \gtrsim (\hat{r})^3 \tag{28}$$

For purposes of illustration, suppose that, for $r_{cutoff} = 0.75\mu$,

$$\begin{aligned}\hat{r} &\cong 0.6\mu\\ (\widehat{r^2})^{1/2} &\cong 0.65\mu\\ (\widehat{r^3})^{1/3} &\cong 0.7\mu\end{aligned} \tag{29}$$

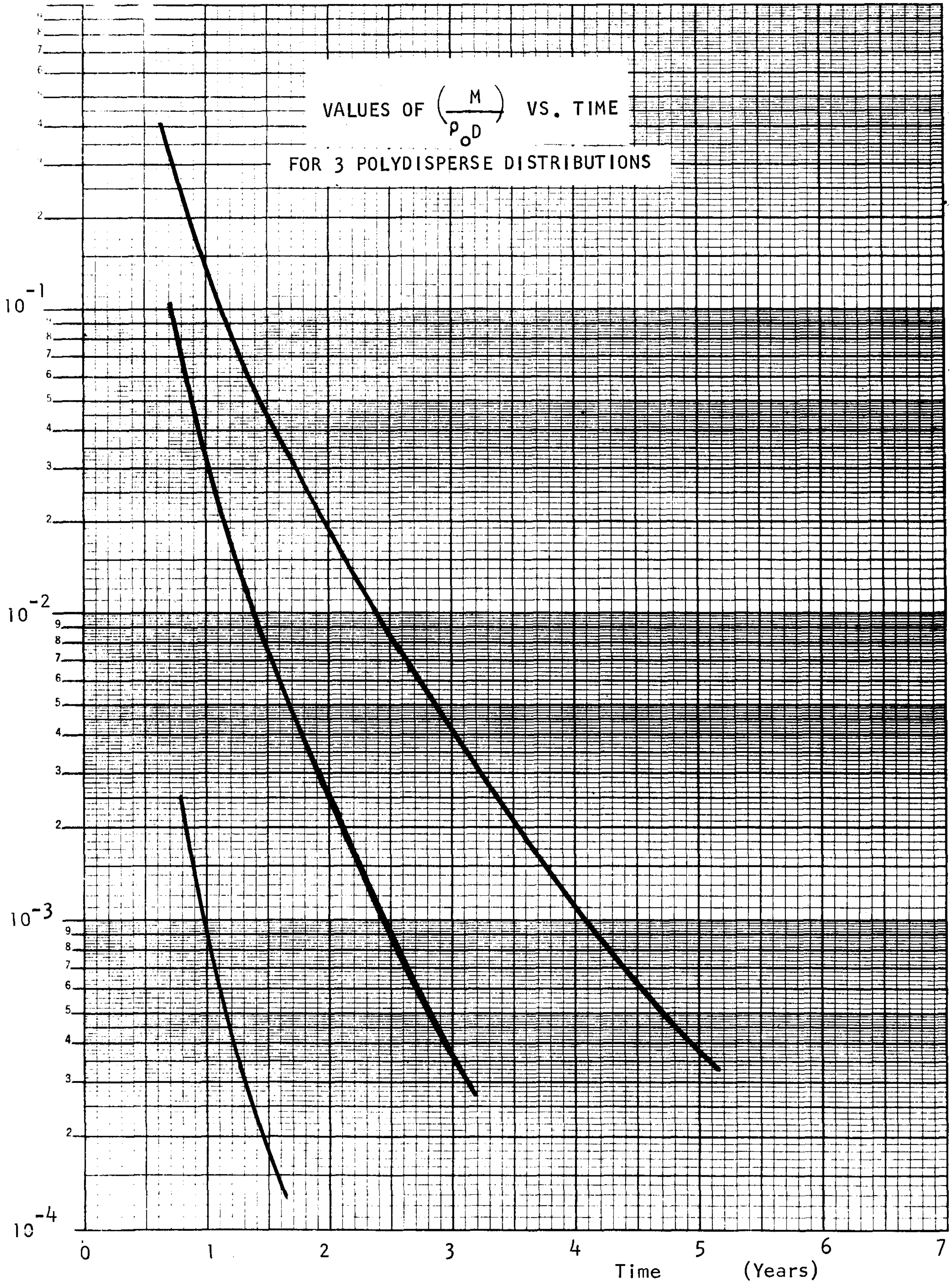
The total residual volume of material in the unit cylinder required to produce an effect M = 0.1 at time t = 1 year will evidently be

$$V(t=1) \approx \frac{4\pi}{3}(0.7)^3\, \rho_o D \approx 6.4 \times 10^{-5}\ \text{cm}^3 \tag{30}$$

The total initial volume of material needed to leave the above residue will, of course, be

$$V(t=0) = \rho_o D\, \frac{4\pi}{3} \int_0^{\infty} \eta_o(r)\, r^3\, dr \tag{31}$$

FIGURE C.3



VALUES OF $\left(\frac{M}{\rho_o D}\right)$ VS. TIME FOR 3 POLYDISPERSE DISTRIBUTIONS

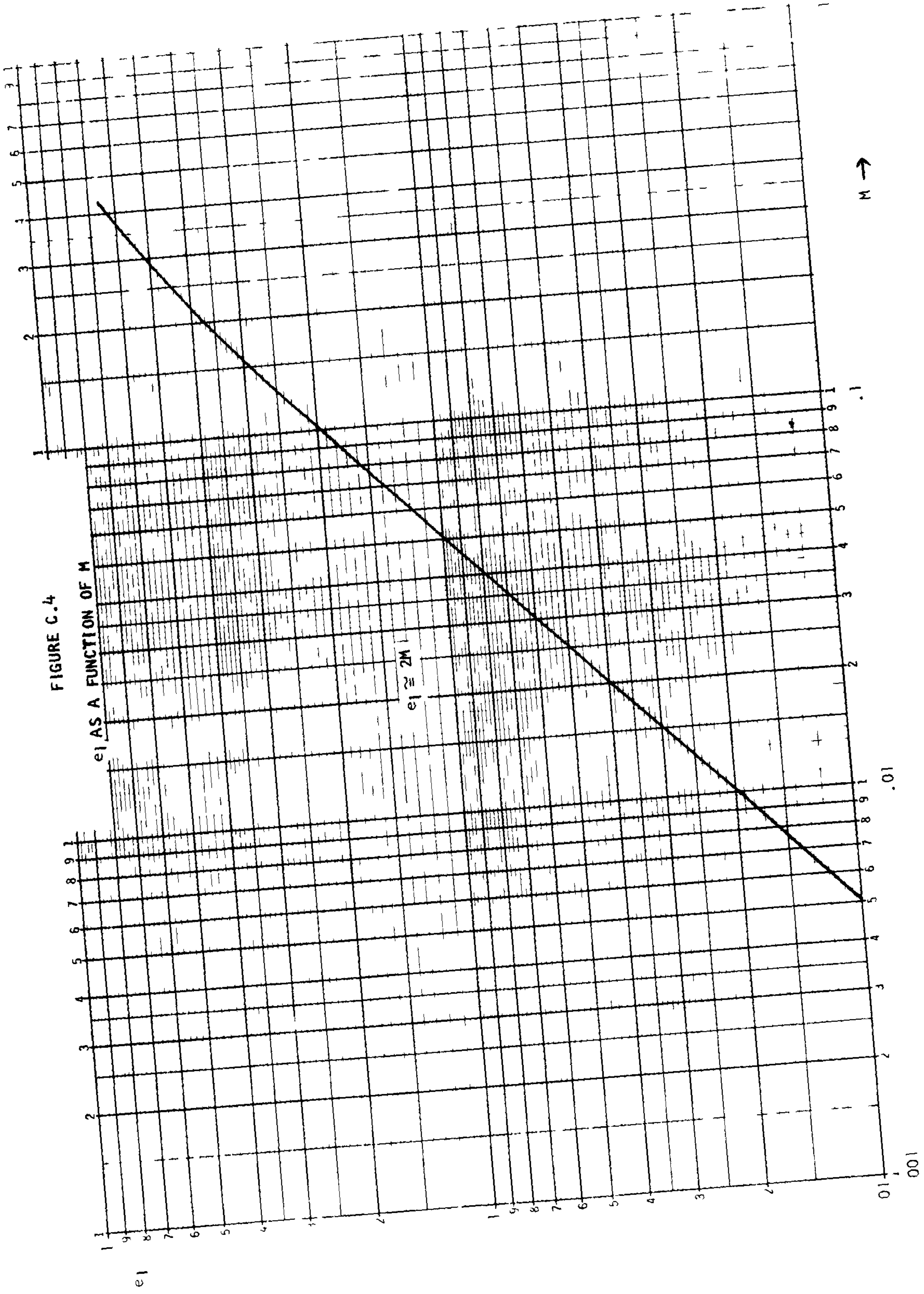


FIGURE C.4

e_1 AS A FUNCTION OF M

Assuming the log-normal distribution of particle sizes $\eta_o(r)$, one easily obtains the volume of material needed to produce M = .1 in a vertical tube of cross-section 1 cm^2, assuming $r_o = 1\mu$ and $\sigma = 0.69$.

$$V(t=0) \quad \frac{4\pi r_o^3}{3} \exp\left(\frac{9}{2}\sigma^2\right) \rho_o D \cong 2.25 \times 10^{-3} \text{ cm of material} \tag{32}$$

The ratio of the two volumes for $r_o = 1\mu$ is:

$$\frac{V(t=1)}{V(t=0)} \cong 2.85 \times 10^{-2} \tag{33}$$

For the other two cases, $r_o = 2\mu$ and $r_o = 5\mu$, the appropriate multiplying factors for (32) are 8 and 125. Thus: if the initial polydisperse particle-size distribution is as given, the model predicts that roughly 3% volume of the original material would remain in the stratosphere at the end of one year. The volume of the residual dust actually contributing to the scattering loss (at time t = 1) is only 6.4×10^{-5} cm^3 per cm^2 of area, which amounts to only .36 km^3 or .087 mi^3 over the entire earth. If the original dispersoid contained a substantial fraction (by volume) of very small particle sizes, it is possible that very noticeable climatic effects might result from the injection of comparatively modest quantities of dust.

To summarize: Figure C.4 shows e_1 as a function of M, which can be determined from equation (23) in general, or read from Figure C.3 for the specific case calculated in Appendix B and a specific choice of $\rho_o D$. The other components of the earth's thermal balance are given by equations (7, 8, 9) in terms of the unknown proportionality constant $X(e_1)$. A heuristic argument was presented which suggested that $X(e_1)$ might be roughly constant and equal to about 0.96; however, the choice is critical if any conclusions are to be drawn about the atmospheric water cycle (evaporation/precipitation) and the subject deserves a deeper and more rigorous analysis.

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APPENDIX D

A MODEL FOR SYNERGISTIC INTERACTIONS

1. Introduction

Consider a generalized population and two biologically active "agents" A, B. If the net effect on the population of the two agents acting together is not a simple sum of their separate effects, then their joint action is said to be synergistic. The case where the two agents A; B mutually enhance each other, is called potentiation. The reverse case, mutual inhibition, is called de-potentiation.* In order to make the above definition precise enough to use in a mathematical model, we assume that all (relevant) symptomatic responses can be quantified on a scale of increasing lethality, by means of a one-to-one correspondence with the real numbers from zero to infinity. Zero might correspond to "no detectable response," while infinity might correspond to "instantaneous death." The correspondences in between can be fixed by any convenient set of criteria. We shall return to this point later.

Of course, there are many possible effects of biologically active agents which do not fit naturally into such a framework. Most drugs, for instance, have very specific purposes: e.g., motor depressants, analgesics, narcotics, anesthetics, cardiac stimulants, analeptics, laxatives, antibiotics, etc. However, they can also be thought of secondarily as generalized physiological "insults." Every drug is, to some extent, toxic.**

Of course, the generalized agents A,B need not be chemical in nature. For example, A might be ionizing radiation and B might be a pathogen. Thus, the effects of radiation or disease resistance could be described in terms of synergistic A,B interactions. Or A may be one pathogen and B another. It is of especial interest to consider the consequences of multiple insults on an ecosystem, e.g., radiation, fire, drought or windstorm followed by insect outbreaks in a forest.

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*This terminology is used in pharmacology in discussing the actions of mixtures of drugs given together.[1]

**The ratio of the effective dose (as a specific antidote) to the toxic dose is defined as the pharmaceutical effectiveness. The higher this ratio, the better; however, the ratio is seldom, if ever, high enough to be absolutely safe under all circumstances for every member of the population. Hence, when some drug B is administered as an antidote for some other generalized "insult," A--whether it be physical, chemical or biological--the situation can be described abstractly as a case of synergistic de-potentiation from the standpoint of over-all lethality to the population.

2. Model for Response to A and B, Administered in Succession

For a wide variety of possible agents "A," it is reasonable to assume a log-normal distribution of responses:

$$\varphi(X;\ \lambda, X_A)\,dX = \frac{1}{\lambda\sqrt{2\pi}} \exp\left\{-\frac{1}{2\lambda^2}\left(\ln\frac{X}{X_A}\right)^2\right\} d\ \ln X \qquad (1)$$

The variable X is, of course, an index of the physical response of the population to the agent; X_A represents the centroid of the distribution or responses (i.e., the value of X where it peaks), while λ is a measure of the "spread" of the distribution.

The assumption (1) is taken to be the fundamental one for present purposes. However, it can be derived in special cases from another starting point. For example, suppose "A" is a substance, such as a drug or toxin, which will not reproduce itself in the host. The concept of dose is meaningful in this case. If one assumes (a) that the distribution of dosages among the population is log-normal and (b) that the distribution of responses to a given fixed dose is also log-normal, then it can be shown easily that the over-all distribution of responses will be of the form (1). However, we wish to assume (1) even when A is a self-reproducing pathogen or pest, whence the "dosage" concept is irrelevant.

Suppose that some generalized insult A has been administered to the population, with a resulting over-all distribution of symptomatic responses as in equation (1). Suppose, further, that a second generalized insult B is administered subsequently, such that the susceptibility of a member of the population to B depends on its general state of health, which is indexed by a characteristic value of X; i.e., the larger X, the sicker and more susceptible to B the individual will be.

This assumption appears reasonable for a number of likely A, B combinations but it is admittedly not perfectly general. It is particularly applicable to cases where B is both ubiquitous and self-reproducing, e.g., an infectious disease or insect pest, whence the initial (infective) dose of B is unimportant or even meaningless. It would also apply where B is not self-reproducing, but constant or nearly constant doses are administered to the population.

The details of the mechanisms whereby B causes damage need not be specified further. It is sufficient to know the mortality (to "B") as a function of previous state of health. Mortality curves are typically "S" curves, which can be interpreted as integrated frequency distributions or "susceptibility" distributions.[2]

If we assume a hypothetical frequency distribution has the standard log-normal form, e.g.,

$$\varphi(X;\ \eta, X_B)dX = \frac{1}{\eta\sqrt{2\pi}} \exp\left[-\frac{1}{2\eta^2}\left(\ln\frac{X}{X_B}\right)^2\right] d\ \ln X \qquad (2)$$

the mortality due to B, $M_B(X;\ \eta, X_B)$ will be given by

$$\begin{aligned} M_B(X;\ \eta, X_B) &= \int_0^X \varphi(X', \eta, X_B)\, dX' \\ &= \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{1}{\eta\sqrt{2}} \ln \frac{X_B}{X}\right)\right] \qquad X < X_B \\ &= \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{1}{\eta\sqrt{2}} \ln \frac{X}{X_B}\right)\right] \qquad X > X_B \end{aligned} \tag{3}$$

Equation (3) will be taken as the "canonical" form for mortality where X is a measure of previous health or resistance (rather than "dose," which is the more familiar independent variable). This is a more appropriate interpretation for situations in which dose is irrelevant or undefinable, as where an infectious disease or a pest is involved.

Example: Insect Attacks on Jeffrey-Ponderosa Pine

The "states-of-health" of pine trees, defined in terms of observable symptoms, have been related to a numerical scale by a system suggested originally by F.P. Keen[3] and since refined and revised by Salman and Bongberg.[4] By noting the condition of needles, twigs, top crown and various miscellaneous factors, a forester can place each tree into one of four "risk classes" as follows:

Risk Class	Penalty Score
I	0
II	1-4
III	5-7
IV	> 8

where the penalties are assessed according to the following scheme.[5]

Table D-1

Penalty System for Rating High-Risk Trees
(Eastside Ponderosa & Jeffrey Pine)

	Penalty
A. Needle Condition	
1. Needle Complement	
a. Needle complement normal	0
b. Less than normal complement through crown. No contrast between upper and lower crown	2
c. Thin complement in upper crown, normal in lower crown. Contrast evident between upper and lower crown	5

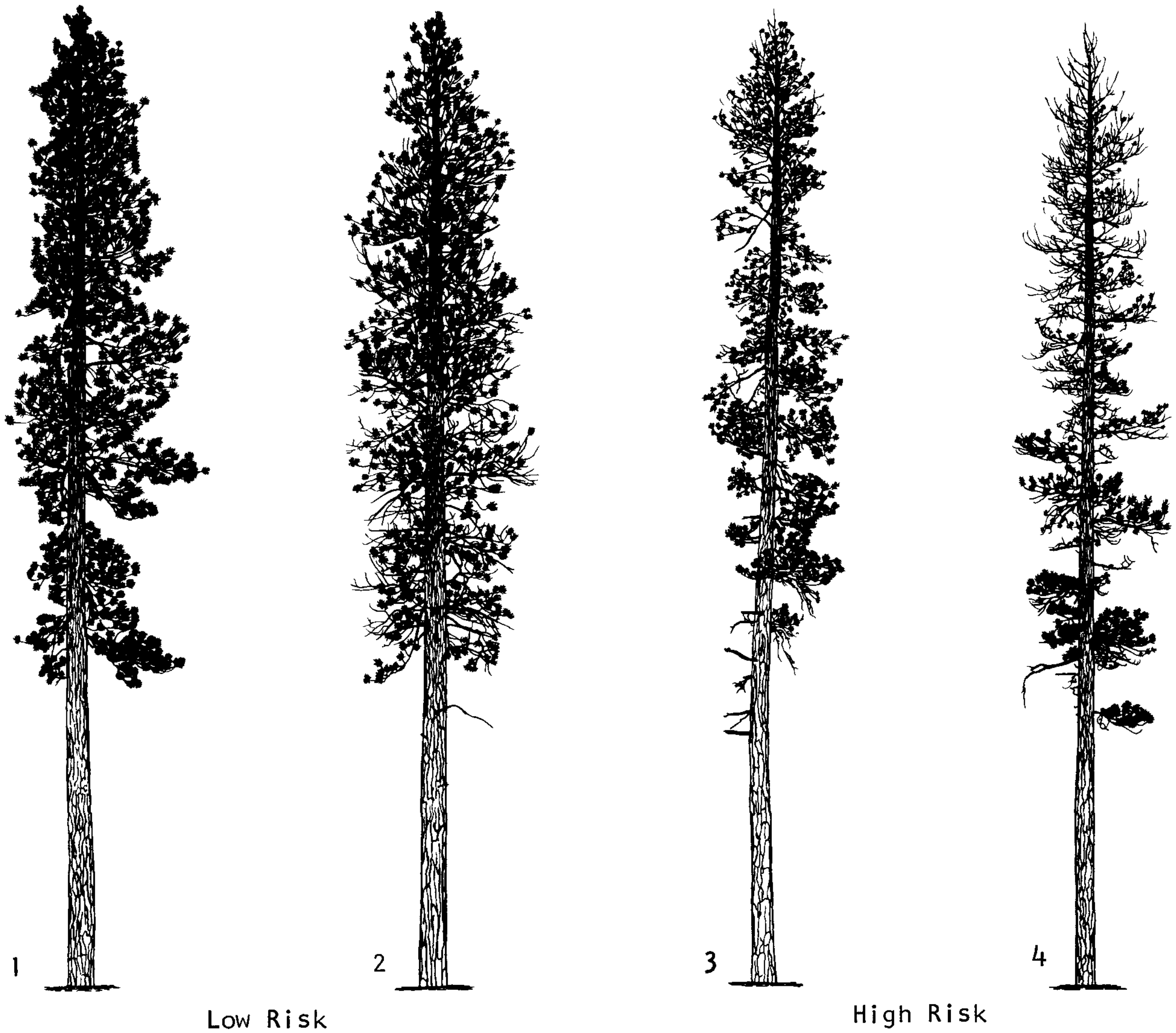
	Penalty
A. Needle Condition (Continued)	
2. Needle Length	
a. Needle length normal	0
b. Needles shorter than normal throughout crown. No contrast between upper and lower crown	2
c. Needles short in top, normal below. Marked contrast	5
3. Needle Color	
a. Normal	0
b. Off color	2
c. Fading	8
B. Twig and Branch Conditions	
1. No twigs or branches dead	0
2. A few scattered dead or dying twigs or branches in crown	1
3. Many scattered dead or dying twigs or branches in crown	2
4. Dead or dying twigs or branches in crown forming a definite weak spot or hole in crown, notably in top 1/3 of crown	3
5. Dead or dying twigs on branches in crown forming more than one weak spot or hole in crown, notably in top 1/3 of crown	5
C. Top Crown Condition	
1. No top killing	0
2. Old top kill with no progressive weakness or killing in green crown	2
3. Old top kill with a progressive weakness or killing in green crown below	5
4. Current top killing	8
5. Broken top--recent, less than 1/3	5
6. Broken top--recent, more than 1/3	8
7. Broken top--old. No progressive weakness	2
D. Other Factors	
1. Lightning strikes--recently struck, no healing evident.	8
--healed strike	2
2. *Dendroctonus valens* attacks in base--current successful	6
--old pitched out...	2

The following factors have local significance and will vary by area. We have little information on their importance, and the marker should weight these in light of his local observation and experience.

3. Mistletoe
4. Needle scale (various species)
5. Needle blight (*Elytroderma deformans*)
6. Rust (*Cronartium* sp.)

FIGURE D.1

DEGREES OF RISK IN PONDEROSA PINES



The penalty score above may be taken to correspond crudely with the response variable X. The distribution of green trees in the various risk groups has been determined for a sample of 18,056 trees in the Lassen and Modoc National Forests, as follows.[6]

Table D-2

Tree Mortality by Risk Class

Risk Class	Number	% of Total	Number Killed by Insects	% of Risk Class
I	12,184	67.5	16	.13
II	3,865	21.4	27	.70
III	1,099	6.1	43	3.91
IV	908	5.0	178	19.71
	18,056		264	

One can work backwards at this point and postulate a single generalized imaginary toxic substance which produces the foregoing observed distribution $\varphi(X)$ of responses.* Thus

$$\int_0^{X_1} \varphi(X)dX = \frac{1}{\lambda\sqrt{2\pi}} \int_0^{X_1} \exp\left[-\frac{1}{2\lambda^2}\left(\ln\frac{X}{X_A}\right)^2\right]\frac{dX}{X} = 0.675 \quad (X_A<1) \qquad (4)$$

$$\int_{X_1}^{X_2} \varphi(X)dX = \ldots = 0.214 \qquad (5)$$

$$\int_{X_2}^{X_3} \varphi(X)dX = 0.061 \qquad (6)$$

In addition to the above three independent conditions one can arbitrarily specify any one of the points X_1, X_2, X_3 (thereby eliminating multiplicative scale factors). Hence, let $X_1 = 1$.

Making the usual change of variables

$$w = 1/(\lambda\sqrt{2})\ \ln\ (X/X_A) \qquad (7)$$

---

*Alternatively, the agent A can be thought of in this case as "the stress of ordinary life."

The integral conditions become:

$$\frac{1}{\sqrt{\pi}}\int_{-\infty}^{-\frac{1}{\lambda\sqrt{2}}\ln X_A} e^{-w^2}dw = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left[-\frac{1}{\lambda\sqrt{2}}\ln X_A\right] = 0.675 \tag{8}$$

$$\begin{aligned}\frac{1}{\sqrt{\pi}}\int_{\frac{1}{\lambda\sqrt{2}}\ln X_A}^{-\frac{1}{\lambda\sqrt{2}}(\ln X_2 - \ln X_A)} e^{-w^2}\,dw &= \frac{1}{2}\,\mathrm{erf}\left[\frac{1}{\lambda\sqrt{2}}(\ln X_2 - \ln X_A)\right] \\ &\quad - \frac{1}{2}\,\mathrm{erf}\left[-\frac{1}{\lambda\sqrt{2}}\ln X_A\right] = 0.214\end{aligned} \tag{9}$$

$$\begin{aligned}\frac{1}{\sqrt{\pi}}\int_{\frac{1}{\lambda\sqrt{2}}(\ln X_2 - \ln X_A)}^{\frac{1}{\lambda\sqrt{2}}(\ln X_3 - \ln X_A)} e^{-w^2}dw &= \frac{1}{2}\,\mathrm{erf}\left[\frac{1}{\lambda\sqrt{2}}(\ln X_3 - \ln X_A)\right] \\ &\quad - \frac{1}{2}\,\mathrm{erf}\left[\frac{1}{\lambda\sqrt{2}}(\ln X_2 - \ln X_A)\right] = 0.061\end{aligned} \tag{10}$$

These relations simplify to

$$-\frac{1}{\lambda\sqrt{2}}\ln X_A = 0.321 \tag{11}$$

$$\frac{1}{\lambda\sqrt{2}}\ln X_2 = 0.542 \tag{12}$$

$$\frac{1}{\lambda\sqrt{2}}\ln X_3 = 0.842 \tag{13}$$

One more independent relation is needed to determine the unknowns.

We have thus (implicitly) determined the parameters of the log-normal distribution φ of the (tree) population among "states of health" X. The next step is to find the mortality due to "B" as a function of the same variable. In the present case "B" represents attacks by insect pests, although it might be any of a variety of insults. According to our model, the mortality as a function of X must be of the form (3), since "susceptibility" is assumed to be given by a log-normal function. Hence joint mortality due to "A" and "B" together is given by

$$\begin{aligned} M_{AB} &= \int_0^\infty \varphi(X;\ \lambda, X_A)\ M(X;\ \eta, X_B)\ dX \\ &= \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{1}{\zeta\sqrt{2}}\ \ln \frac{X_A}{X_B}\right)\right] \qquad X_A < X_B \\ &= \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{1}{\zeta\sqrt{2}}\ \ln \frac{X_A}{X_B}\right)\right] \qquad X_B < X_A \end{aligned} \tag{14}$$

where

$$\zeta = \sqrt{\lambda^2 + \eta^2} \tag{15}$$

The data in Table D-2 imply

$$M_{AB} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{1}{\zeta\sqrt{2}}\ \ln \frac{X_B}{X_A}\right)\right] = 0.0146 \tag{16}$$

which reduces to

$$\frac{1}{\zeta\sqrt{2}}\ \ln \frac{X_B}{X_A} = 1.542 \tag{17}$$

which is analogous to (11-13). These four relations can be thought of as fixing four of the six parameters, for given values of the other two.

In principle, one can also extract two more equations from the data in Table D-2, thereby determining the parameters completely. In practice this procedure would certainly be unwarranted since (a) the data is not as unambiguous as one might wish,* and (b) it would lead to inconsistencies unless nature conforms exactly with the model. It is more illuminating to under-utilize the available data and present some of the results in functional form.

For instance, suppose the "dose" of agent A is increased such that the median point X_A is raised to X'_A, but the dispersion λ (which is basically a characteristic of the population) remains unchanged. This could occur, for instance, if some new environmental insult, such as a drought or radiation field, were added to the already existing hazards of existence. Once the scale of physiological responses is related by a known one-to-one correspondence to a numerical scale, in a manner analogous to the foregoing discussion of risk classes, the numerical value of X'_A can be determined by a simple census of the fraction of the perturbed population in each class.

---

*The classification procedure depends on human judgment, which of course raises questions about the handling of borderline cases, e.g., by different observers.

Since λ remains unchanged by assumption, and so also does η, it follows that ζ is unaltered and can be determined in terms of the old values of X_B, X_A. Hence, substituting (17) in (14) we obtain

$$M_{AB} = \frac{1}{2}\left[1 - \mathrm{erf}\ 1.542\left(1 - \frac{\ln X'_A/X_A}{\ln X_B/X_A}\right)\right] \qquad (18)$$

with the convention that $\mathrm{erf}(-u) = -\ \mathrm{erf}u$. The argument $1 - \frac{\ln X'_A/X_A}{\ln X_B/X_A} = Q$ is plotted as a function of X'_A/X_A for various values of X_B/X_A in Figure D.2. The joint mortality M_{AB} as a numerical function of Q is shown in Figure D.3. The form of the curve is exactly what one would expect on the basis of qualitative arguments. It is interesting to analyze the curves in terms of the question: for a (given) value of X_B/X_A what must X'_A/X_A be to achieve a specified joint mortality?

M_{AB}	Q
.05	0.77
.10	0.60
.20	0.39
.50	0.00

In the case of $M_{AB} = .50$ we note immediately that the requirement is $X'_A/X_A = X_B/X_A$. Other choices are plotted in Figure D.4.

References

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2. J. H. Gaddum, J. Physiol. 61: 141-150, 1926.

3. F. P. Keen, J. Forestry 34: 919, 1936.

4. K. A. Salman and J. W. Bongberg, J. Forestry 40: 533, 1942.

5. Based on Salman and Bongberg, revised by R. C. Hall, 1956.

6. Salman and Bongberg, op. cit.

FIGURE D.2

Q AS A FUNCTION OF $\frac{X_B}{X_A}$ AND $\frac{X'_A}{X_A}$

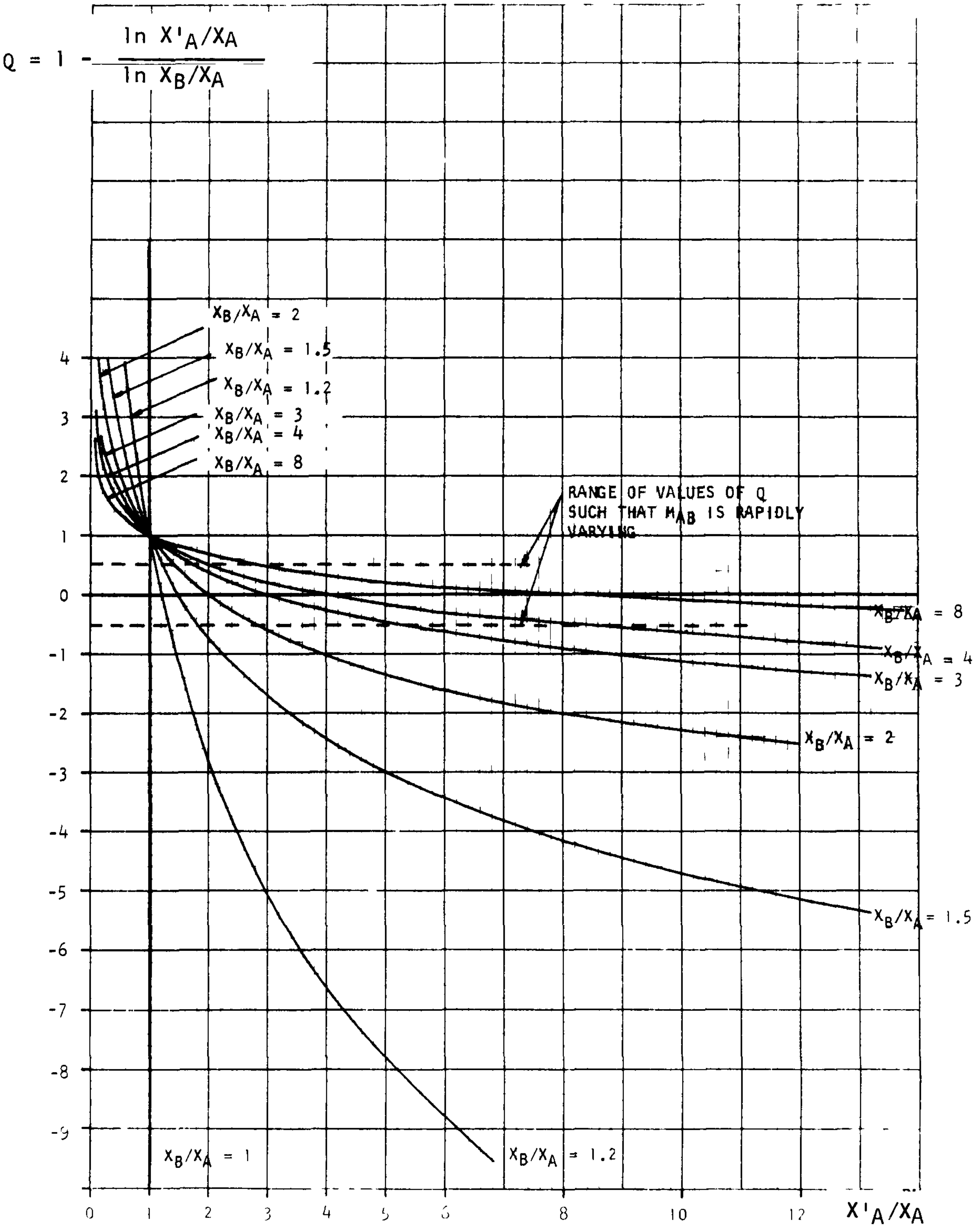


FIGURE D.3

MORTALITY AS A FUNCTION OF Q

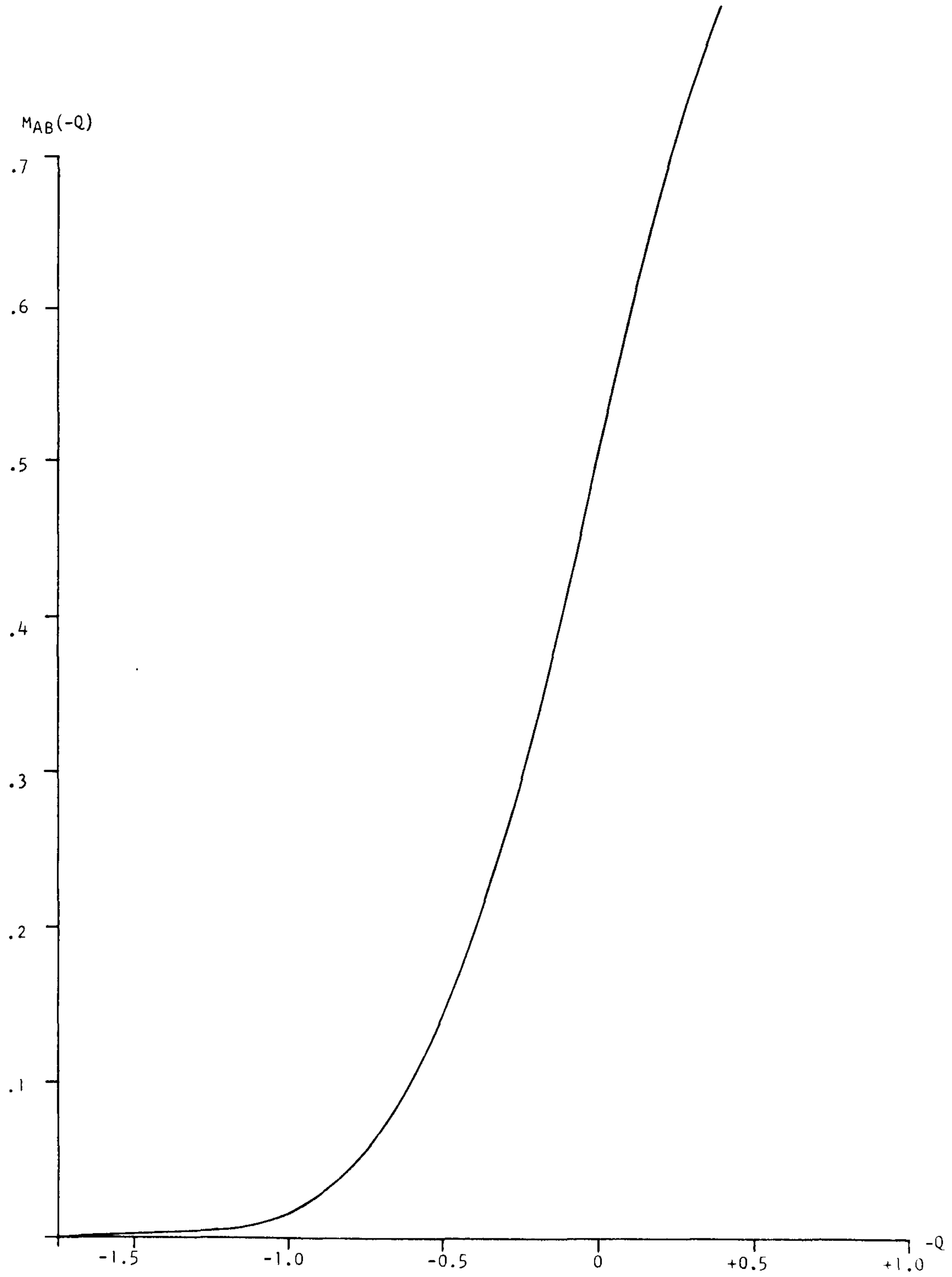
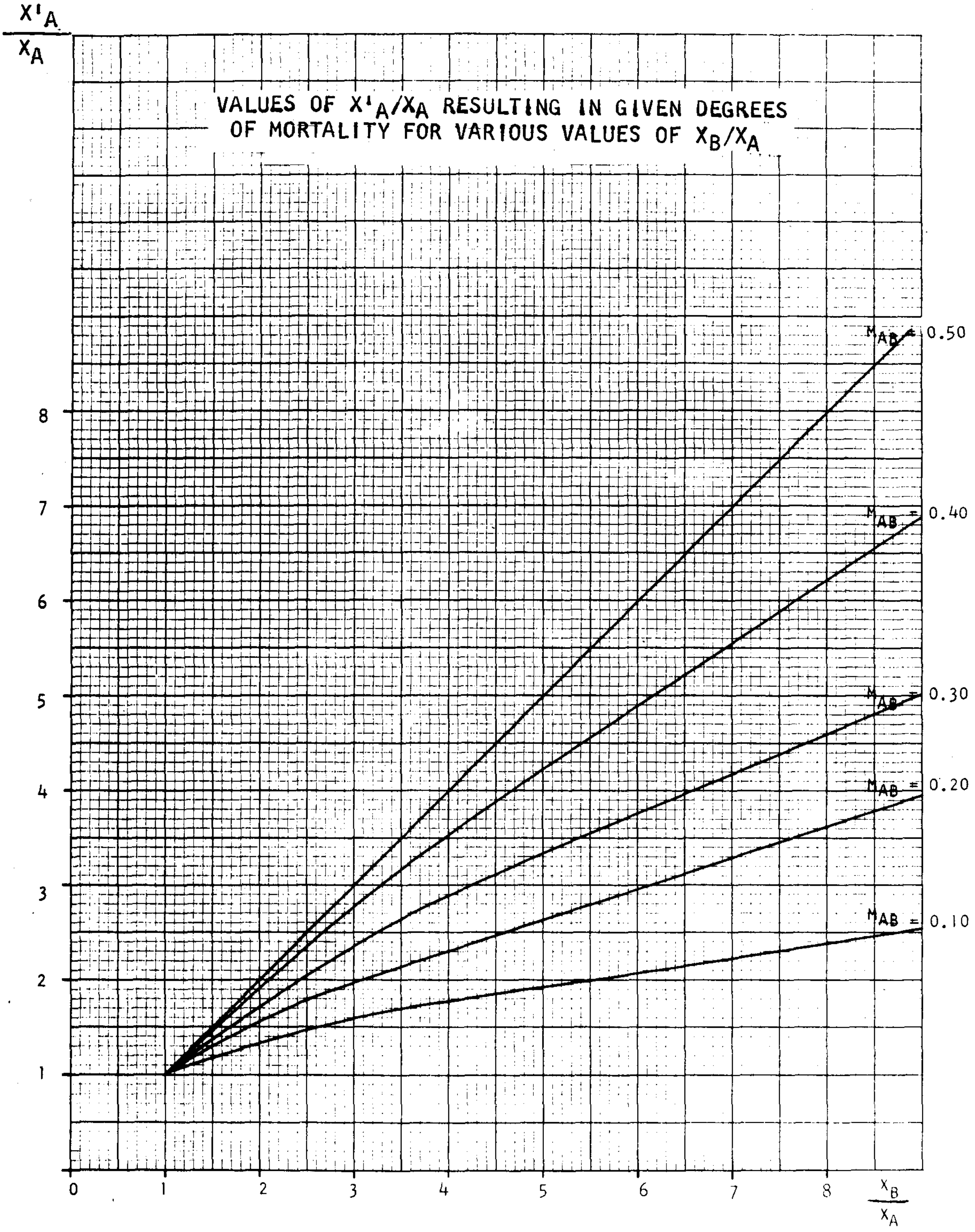


FIGURE D.4


$\frac{X'_A}{X_A}$
VALUES OF X'_A/X_A RESULTING IN GIVEN DEGREES OF MORTALITY FOR VARIOUS VALUES OF X_B/X_A
M_{AB} = 0.50
M_{AB} = 0.40
M_{AB} = 0.30
M_{AB} = 0.20
M_{AB} = 0.10
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
$\frac{X_B}{X_A}$

APPENDIX E

NATURAL ANALOGS OF NUCLEAR ATTACK

The purpose of this section is to present in one place data on various large-scale natural disturbances in order to make possible some meaningful comparisons with thermonuclear weapons. The simplest parameter which can be used for this purpose is total energy release. We shall supplement this with a discussion of the partition of energy into different channels, e.g. seismic waves, water waves, air waves, heat and convection, etc. Much of the discussion is incomplete, reflecting lack of data, trustworthy theory, or both. However, the results should be of sufficient interest to outweigh the obvious shortcomings.

For simplicity we shall measure energy in units of megatons, noting that

$$1 \text{ MT} = 10^{15} \text{ calories} = 4.186 \times 10^{22} \text{ ergs.}$$

No emphasis has been attached to casualties or damage done by the catastrophes listed hereafter, since this is largely fortuitous. As a matter of interest we might mention that the Chinese earthquake of 1556 was probably the most destructive single event, with 830,000 estimated dead. The Tokyo-Yokohama earthquake of 1923 probably comes second, with 311,564 persons killed (mostly by fires) or missing. Another Chinese earthquake in Kansu province, December 16, 1920, killed about 200,000, mostly due to landslides and floods. Many other earthquakes have taken huge tolls including Lisbon (1955), Chile (1960), etc.

Volcanoes come next in destructiveness. The eruption of Vesuvius in 79 A.D. which buried Pompeii and Herculanéum was one well-known example. The eruption of Asamayama (1783) in Japan probably killed the most people, followed by Tomboro (1815) which took 56,000 lives, Krakatoa (36,000), Mt. Pelée (30,000) and others.

Storms also have occasionally taken many thousands of lives, especially in Bengal and Assam (India) but this is exceptional. There are no known fatalities attributable to meteorites. Forest fires have not produced many casualties as a rule except where towns have been caught in the path, as Peshtigo, Wisconsin was in 1871. City fires have been extremely destructive, of course. The incendiary attack on Dresden cost an estimated 135,000 lives, which was exceeded only by the Tokyo-Yokohama fires of 1923.

Table E-1

Earthquakes

Location	Date	Magnitude (M)	Fault Length (km)	Energy (MT)	Tsunami (?)
Wei-Ho Valley, China[1]	Feb. 2, 1556	9(?)*	--	6500	No
Colombia-Ecuador	Jan. 31, 1906	8.9	--	5000	Yes
Sanriku, Japan	Mar. 3, 1933	8.9	--	5000	Yes
Portugal-Morocco (Lisbon)	Nov. 1, 1775	8.75(?)	750(?)	3500	Yes
Assam, India	Aug. 15, 1950	8.6	--	2000	--
Assam, India	June 12, 1897	8.6	--	2000	--
Yakutat, Alaska	Sept.10, 1899	8.6	150 (6 faults)**	2000	Yes
Concepción, Chile	May 22, 1960	8.5	1200	1500	Yes
Mino-Owari, Japan	Oct. 28, 1891	8.4	450 (3 faults)	1000	--
Kwanto (Tokyo-Yokohama), Japan	Sept. 1, 1923	8.3	--	800	Yes
San Francisco, California	Apr. 18, 1906	8.25	420	700	--
New Madrid, Missouri	Dec. 16, 1811	8.1(?)	250	400	No

These M values come mostly from Richter (1958).[2] Magnitudes quoted in the literature disagree considerably. We have chosen those propounded most frequently or with most emphasis. Note that elsewhere[3] Sanriku has been given a magnitude of 8.3 and Colombia-Ecuador as 8.6, even though the magnitude (M) is supposed to be a measured quantity which can be determined exactly (in principle) from seismographic measurements. The difficulties of making such measurements and the ambiguities inherent in normalizing them to a common standard are probably more than sufficient to explain occasional discrepancies of ± 10%. Unfortunately, the energy released by an earthquake is usually assumed to depend logarithmically on the magnitude, e.g.,

$$\log_{10} E = \alpha + \beta M - C^{***}$$

Again, different authorities prefer widely varying choices for α and β, based on different estimates of the amount of strain energy released by a seismic event of magnitude 8. A brief search of the literature quickly uncovered the following choices:

α	β
12	1.8 (4)
11.8	1.5 (5)
11.4	1.5 (6)
13	1.5 (7)

---

*Greatest loss of life from any earthquake (830,000 dead). Covered a large area, most of 3 provinces: Shensi, Shansi, and Honan.

**Greatest vertical displacement (50 feet) ever recorded.

***$C = \log_{10} (4.186 \times 10^{22}) = 22.62$. This factor arises from converting ergs to MT's.

It is obvious that the range of errors for the energy values given are rather large--probably at least an order of magnitude. One difficulty is that earthquake energy is almost certainly a linear function of fault length L since there is a limit to the amount of strain-energy which can be contained in a given volume of rock. For example, the approximate relation

$$E = .78L$$

was obtained by a least-squares fit of magnitude vs. fault length data in which there was a lot of scatter.[8] Magnitude, on the other hand, depends not only on L but on focal depth D, on the elastic properties of the strata, and the "coupling" between neighboring blocks of the earth's crust. The latter could very well be the big uncertainty. Rather than measuring the amplitude of the first ground-wave received by the seismograph, it might be better to integrate the intensity of all signals received over a finite time interval. This would seem to be a more accurate measure of the "perceived magnitude" of the shock and might be a more reliable guide to the energy involved.

The above remarks may illumine a difficulty which seems to arise when earthquakes are compared to underground nuclear explosions. For such detonations, only about half the energy yield takes the form of blast and shock: the remainder is heat and radiation, both of which remain confined near the ground zero. Peak acceleration of the ground seems to scale as

$$.00014\ gE^{3/4}\ d^{-2}$$

where g is the normal acceleration of gravity, E is the yield in MT's, and d is the distance in km from the epicenter.[9] Even an energy yield of 10^4 would produce only about 1/700 g peak acceleration at a distance of 10 km. According to one Nevada experiment (RAINIER), 1.7 KT underground burst with 50% of its energy going into blast and shock waves is equivalent to an earthquake of magnitude 4.07 which would be consistent with an assumed strain energy release of 10^{19} ergs or about .25 KT. On the other hand, a seismic disturbance of magnitude 4 should be perceptible to observers at a distance of about 100 km, whereas RAINIER itself was detected by only a few people at a distance of about 4 km where the measured peak acceleration was .02 g. Thus there is evidence that either nuclear explosions produce ground shocks of an altogether different pattern from earthquakes, or else that the actual energy released by earthquakes has hitherto been underestimated. In view of the apparent difficulties of distinguishing seismic waves from the two sources (ergo Project VELA), the latter seems not unlikely. To bring the energy figures into rough coincidence for magnitude 4, one must multiply the earthquake figure by about 3.5. Even so, it is difficult to reconcile the apparent differences in perceptibility, which are hard to explain unless underground bursts dump proportionately much less energy into long-waves and more into the initial pulse.

Tsunamis

Tsunamis are water waves occurring in conjunction with earthquakes and probably arising from sudden displacements along fault lines, or associated mudslides underwater.

Tsunamis are classified m = -1, 0, 1, ---4 where m = 4 corresponds to a wave about 100 feet (30m.) high. In terms of magnitudes Iida[10] finds the empirical relation

$$m = 2.61\ M - 18.44$$

whereas Wilson[11] prefers

$$m = 2M - 13.5.$$

The proportion of seismic energy converted into tsunami energy is the subject of considerable disagreement. Iida estimates 10%, but others believe the figure is much smaller. Wilson's preferred estimate is

$$E_t \cong .0063\ E$$

which implies a rather small coupling (or a rather considerable phase "mismatch") between the earth movements and the water. The height of the tsunami wave (at the shore line) seems to vary logarithmically with m,[12]

$$\log_{10} H = 0.375\ m$$

Some large tsunamis are listed below.

Table E-2

Tsunamis

Location	Source	Date	M	H(Meters)
Kamchataka*	Kurile trench?	Oct. 6, 1737	--	65
Merak, Java	Krakatoa	1883	--	42
Sanriku	Tuscorora deep	June 15, 1896	--	30
Sanriku	Tuscorora deep	Mar. 3, 1933	8.9	23
Lisbon	Offshore mudslides?	Nov. 1, 1775	8.75(?)	16
Chile	Offshore mudslides	May 22, 1960	8.5	--
Kamchataka	Kurile trench	Nov. 4, 1952	8.4	--
Kaui	Aleutians	Apr. 1, 1946	--	16

Since observations of wave height are made on shore at varying distances from the focal point of the disturbance, along coasts of varying configurations, the observed heights are not accurate measures of the energy of the initial disturbance.

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*This seems to have been the highest on record.[13]

VOLCANOES

Volcanic eruptions occur with varying degrees of explosiveness. The least explosive variety, typified by Mauna Loa on Hawaii, has almost nothing in common with thermonuclear explosions. Large quantities of lava simply pour out of the mountain from time to time and gradually solidify on the slopes.

The most explosive type, as illustrated by Krakatoa, produces blast effects and fallout analogous to nuclear weapons. Insofar as the mechanism leading to an eruption is currently understood, the difference between the two types seems to originate in the composition of the magmatic material. As the liquid magma rises toward the surface it begins to cool, and crystallization begins. Some of the more volatile components (CO, CO_2, H_2, H_2O, H_2S, etc.) hitherto held in solution may be trapped in the crystal structure. However, the excess is forced out of solution and the magma becomes charged with gas under high pressure which provides the motive force for the eruption. If the excess volatile component is small the lava will simply flow, but with a higher percentage of compressed gas present, the cohesive forces of the magma will be overcome and the result is an explosive release of pressure. It is noteworthy that the index of "explosiveness" tends to be similar for a given volcano at different times and also for different volcanoes in the same region. This is consistent with the theory since nearby volcanoes may be tapping common underground sources of magma. The most explosive volcanoes are those in Indonesia (Krakatoa, Tomboro), Japan (Asamayama, Sakurajima), and Central America (Coseguina, Santa Maria, etc.).[14]

The total heat energy released by an eruption depends only on the cubic volume of matter expelled and its original temperature and heat capacity. However, the explosive component depends on the fraction of volatile substances originally held in solution. There is almost no way to obtain this for a given case, although laboratory experiments suggest that 4-5% of volatile substances is about the dividing line and some kinds of magma may hold up to 10-15% volatile components in solution until crystallization begins.[15] The remainder of the explosive impulse arises from heat given up by finely divided aerosols or droplets of magma which cool suddenly and adiabatically. This is the source of volcanic "ash."

The explosive energy, not the total heat energy, in each of the cases in Table E-3 could probably be very crudely estimated from either the height of the column of smoke or the distance at which the detonations were heard if the energy release were instantaneous. They would then be compared with Krakatoa (the most explosive case). According to a detailed calculation, due to W. Brown,[16] the total heat energy released was probably in the range 11-32 kilomegatons, while the explosive contribution was probably in the range of 30-50% or 5-15 KMT's. The remainder dissipates more slowly. If the efficiency of transfering energy to the atmosphere is similar to that of a meteorite, then indeed Krakatoa appears to have been 5 to 15 times more powerful than the great Siberian meteorite of 1908 (see METEORITES), consistent with the observations of Whipple[17] and Astapowitsch.[18]

Table E-3

Volcanoes

Volcano, Date	Length of Time	Est. Vol. Cu.Mi.	Area Covered by Ashes Sq. Mi.	Max. Alt. of Smoke Column, Mi.	Max. Dist. Heard, Mi.
Tomboro, Soembawa Apr. 11-12, 1815	2 days	28[a]	-depth of 2' at 850 mi. dist. -72 hrs. darkness at 300 mi.	--	--
Krakatoa, Sunda Straits Aug. 26, 1883	2 days	5	--	~50 mi.[b]	>2,900
Agung, Bali Mar. 17, 1963	--	--	--	33 mi.[c]	--
Asamayama, Japan 1783	--	--	48 villages buried	--	--
Sakurajima, Japan Jan. 12, 1914	2 days	--	--	6 mi. (oblique)	--
Katmai, Alaska June 6, 1912	Apparently instantaneous	5	-depth of 1' at 100 mi. dist. -60 hrs. darkness at 100 mi. dist.	--	> 750
Coseguina, Nicaragua Jan. 20, 1835	3 days	13[d]	-sev. in. at 500 mi. dist. -43 hrs. darkness	--	>1,100
Santa Maria, Guatemala Oct. 24, 1902	--	~1	125,000	18 mi.	> 500
Skaptar Jökull, Iceland[e] June 8, 1783	3 days of gas & ash, then lava	--	-all of Iceland & surrounding sea. >>-100,000 crop acres affected in Norway	--	--

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[a] Estimate from Roy. Soc. Rept. on Krakatoa.[19] Another estimate gives the figure as 50 cu. mi.[20] Tomboro was probably the greatest eruption of historic times.

[b] The main fine dust cloud seems to have peaked at 23 miles, but the column of smoke and ash following the most violent explosion was apparently higher.

[c] Altitude measurements made in northern hemisphere (MacDonald Observatory, Texas).[21]

[d] Estimates range from 4 cu. mi. to 60 cu. mi. The estimate of 13 was made by Rèclus (1891) and used by Sapper[22] in his study of volcanic explosiveness.

[e] Greatest lava flow in history, estimated as the equivalent of Mt. Blanc, or about 45 cu. mi.[23]

Actually the comparison is not easy to make since Krakatoa (like most volcanoes) did not blow up all at once. Explosions were seemingly more or less continuous, punctuated by a few louder bangs. Sound waves from successive detonations interfered so that no well-defined pulse could be identified and analyzed (e.g., by Scorer's technique[24]). Comparisons with nuclear explosions are also considerably complicated by the fact that volcanic eruptions are typically spread out in time, although Katmai may have been exceptional in this regard. It is difficult to estimate how much of the total energy released can be attributed to the two or three single greatest blasts. If indeed, the largest individual explosion comprised as little as 10% of the total energy (500-1500 MT's) for Krakatoa, then it is just barely possible to reconcile its apparent magnitude as compared to that of the Siberian meteorite.

METEORITES

There is no doubt but that the impact of a large meteorite comes closest of all natural events to simulating the blast effects of a thermonuclear explosion, although there are many important differences. If the meteoritic material could be collected and weighed, and the trajectory determined, it would be possible to calculate the exact energy of the original object. In practice, matters are not so simple, since the composition of the original body is unknown, and its trajectory can only be inferred by the angle of collision with the ground. Frozen methane, CO_2, ice and other volatile materials such as might be associated with comets, for example, would, of course, leave no trace of their existence. Velocity of passage through the atmosphere could only be known accurately if observed by radar or astronomical telescopes. Hence, for the vast majority of meteoric events, including all the large ones of interest, it is only possible to give a range, namely from about 7 to 45 miles per second, depending on whether the meteorite moving at roughly 26 miles per second relative to the sun, overtakes the earth (moving at 18.5 miles per second in its orbit), or collides frontally with it. The average velocity of observed meteorites is 10 miles per second, reflecting the fact that most of the swarms are moving around the sun in the same direction as the earth, hence most collisions are of the overtaking variety.

The best evidence for inferring total energy release is, in most cases, the crater. This evidence is indirect, of course, and estimates depend upon theoretical considerations which involve the entire complex process, including the collision, vaporization and recondensation of meteoric material, production and dissipation of shock waves, plastic deformation of the surrounding rock strata, shatter-cone and coesite formation, etc.* It is felt that these processes are now at least qualitatively understood and most of the peculiar desiderata of high velocity impacts can be reproduced on a small scale in the laboratory. One of the most important points on which our inferences will rest is the fact that at extremely high velocities, the resulting crater formation is quite independent of the structure of the target. Actually, the material near the impact point behaves very much as though it were a fluid or a pile of loose dust. This is because the instantaneous pressures generated by the shock waves (from tens of thousands to millions of atmospheres) simply overwhelm all macroscopic cohesive forces and each particle moves independently.

Erosion and sedimentation soon fill in most meteorite craters so the only reliable evidence which remains visible after the passage of long times is the crater diameter, which can be determined by observation of

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*Shatter-cones are unique structures in limestone, sandstone or other conglomerates formed by strong shock deformations originating at a point. Coesite is a crystalline form of silicon (analogous to the diamond form of carbon) formed only by pressures exceeding 20,000 atmospheres--which would normally occur only at depths exceeding 40 miles.[25]

the deformed strata. In recent years many craters of meteoric origin have been identified first from aerial photographs and subsequently confirmed in other ways by the presence of shatter-cones, coesite, or nickel-iron fragments.

At least 39 large fossil craters have now been identified in one or more of these ways, and a number of others are in the "possible" category. In the following table, diameters are "apparent" diameters, disregarding the "lip" of the crater. Energies are extrapolated from the nomogram in Effects of Nuclear Weapons,[26] which relates yield to crater diameter assuming that the semi-empirical relation

$$E = R^{10/3}$$

holds true, where E is the energy yield and R is the crater radius.

Table E-4

Meteorite Craters

Crater Location	Apparent Crater Diameter (feet)	Probable Energy--MT
Vredefort, Transvaal, S. Africa	160,000	2,500,000*
Ries Kessel, Germany	90,000	540,000
New Quebec, Canada	11,500	1,200
Podkamennaya-Tunguska, Siberia	(see next page)	1,000
Jalemzane, Algeria**	5,800	120
Canyon Diablo, Arizona	4,000	36***
Wolf Creek, Australia	2,800	12
Boxhole, Australia	575	0.12
Odessa, Texas	560	0.1
Numerous smaller craters		

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*Dietz[27] estimates 1,500,000 MT but gives no theoretical basis for the estimate. However, in view of the uncertainties, his estimate and ours are extremely close.

**Not a confirmed meteor crater.

***Dietz estimates 5 MT. Moulton,[28] and subsequently Wylie,[29] estimated a velocity of impact between 7-14 mps. Nininger[30] estimated a mass of 10^6 tons. Assuming 10 mps, the energy released would have been about 3×10^{22} ergs or less than 1 MT. It must be remembered that the evidence is extremely tenuous at best and other estimates of the mass of the Canyon Diablo meteorite range from 12,000[31] to 4,000,000 tons![32] At 50 mps, a 4,000,000-ton mass would yield about 3,000 MT, whereas a 12,000-ton body at 7 mps would yield only 200 KT. Our 36-MT estimate is close to the geometrical mean of these two extremes.

Several other interesting meteoric events have taken place which do not fit into the above scheme, since no single crater defines the impact. For example, one might include the famous "Carolina Bays," Campo del Cielo (Argentina), Henbury (Australia), and the two famous Siberian meteors (Tunguska, 1908, and Sikhote-Alin, 1947) and Mt. Kenya (Kenya, E. Africa, 1946).

The Tunguska meteor of June 30, 1908, has aroused great interest because it does not seem to fit the expected pattern. In particular, no large craters were found when the site was investigated (the largest was about 150 feet in diameter, although trees were knocked down in large numbers at a distance of 300,000 feet from the impact point. The sound was heard at a distance of 2,000 miles. Extrapolating from ENW this kind of damage would be expected to accompany a 1000-MT surface burst.* The most detailed analysis made to date,[36] using data collected by Whipple[37] and Astapowitsch[38] from about a dozen independent microbarographic measurements, and comparing with detailed calculations, led to an estimate of 4×10^{24} ergs, or 100 MT as the energy communicated to the atmosphere. Scorer's calculation is consistent with the 1000-MT estimate assuming 10% of the total energy went into atmospheric waves. The above is also consistent with Astapowitsch's comparisons if we replace his crude estimate of the energy of the Krakatoa explosion by our own (see VOLCANOES).

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*The range of error here is large, unfortunately. The data would not be violently inconsistent with an estimate of only 100 MT's. However, Wyatt[33] also accepts the 1000-MT figure, and argues that the best hypothesis covering all known aspects of the Tunguska event is that the "meteor" was actually a small lump of anti-matter. If this were the case, then the explosion would have been <u>in fact</u> of thermonuclear origin. Some very slight confirmation exists in the form of recent contradictory reports of the existence of an abnormal amount of background radiation in the area.[34] A recent article by Cowan, Libby and Atluri has reopened the discussion.[35]

STORMS

Storms release their energy so slowly in comparison with nuclear explosions that their effects are quite dissimilar. The greatest storms are of the hurricane type.* Although there is reason to believe that storms in the western Pacific occasionally reach greater magnitudes, Table E-5, adapted from a list compiled by the Hydrometeorological Section of the U.S. Weather Bureau,[39] indicates the orders of magnitudes involved. Years covered are 1900-1950.

The energy figures were calculated by fitting the storm isobars at sea level to both visually drawn and exponential pressure profiles, and taking up the mean. The deviations between the two types of calculations range up to about 25% in some cases, but the means are probably accurate to about 10% or so. See Figure E.1. For simplicity, the storm is assumed to extend vertically to the top of the atmosphere, the kinetic energy in each layer being simply proportional to the atmospheric density.

During its lifetime a hurricane will, of course, dissipate much more energy than is present in the cyclostropic winds at any given moment. The source of energy is, of course, originally heat from the sun which has warmed large expanses of water to the point that "normal" transport processes cannot get rid of the excess energy as fast as it is being accumulated in the tropical oceans. Hence some turbulent heat transfer mechanism is needed to speed up the process and maintain over-all equilibrium between the tropics and the arctic regions. The mechanism is, roughly, that a large heated air mass rises, creating a low-pressure region. Neighboring air rushes in to fill the "vacuum," but, because of the Coriolis effect produced by the earth's rotation, a circular wind pattern is set up balancing a pressure gradient against centrifugal forces. The moving air transports energy very rapidly by creating waves and tides, and by evaporating and lifting large quantities of water vapor, much of which is carried away to condense and release its latent heat elsewhere, thus rapidly equalizing the imbalance by cooling the tropical oceans and warming the temperate latitudes.

Total energy dissipated is hard to estimate; it depends on the dissipation <u>rate</u> (proportional to instantaneous kinetic energy and to some effective "viscosity" which would require a separate and highly uncertain calculation) and on the hurricane lifetime, which is typically a week or ten days.

---

*Known also as Cyclones (India), Willy-willy's (Philippines) and Typhoons (Japan).

Table E-5

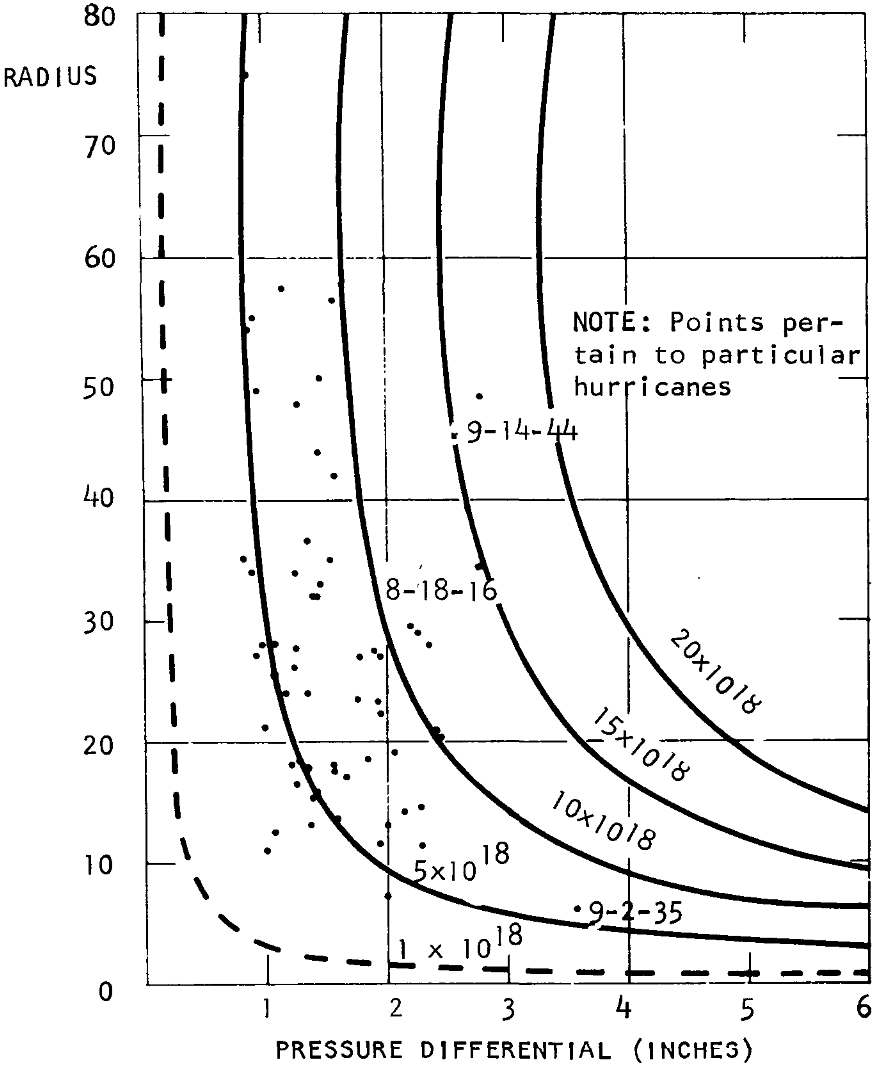
Storms

Place	Date	Radius of Max. Winds Mi.	Velocity of Max. Winds mph.	Min. Central Pressure Inches	Kinetic Energy in a Cylinder 50 Mi. in Radius to the Top of the Atmosphere MT	Kinetic Energy in Cylinder 100 Mi. in Radius MT
Santa Gertrudis, Tex.	Aug. 18, 1916	35	116	28.00	65.02	177.92
Hatteras, N.C.	Sept. 14, 1944	49	113	27.88	56.32	188.16
Key West, Fla.	Oct. 20, 1926	21	112	27.52	54.08	152.32
Brownsville, Tex.	Sept. 5, 1933	30	105	28.02	53.25	164.48
Miami, Fla.	Sept. 18, 1926	24	110	27.59	52.80	151.04
Savannah, Ga.	Aug. 11, 1940	26	77	28.78	48.70	--
New Orleans, La.	Sept. 29, 1915	29	106	27.87	47.36	154.88
Hillsboro, Fla.	Sept. 17, 1947	19	102	27.76	44.86	--
West Palm Beach, Fla.	Aug. 26, 1949	22	99	28.16	43.52	--
Long Key, Fla.*	Sept. 2, 1935	6	137	26.35	43.39	--
Long Key, Fla.	Sept. 28, 1929	28	98	28.18	43.07	--
Homestead, Fla.	Sept. 15, 1945	12	99	28.09	41.22	--
Galveston, Tex.	Sept. 8, 1900	14	104	27.64	39.42	--

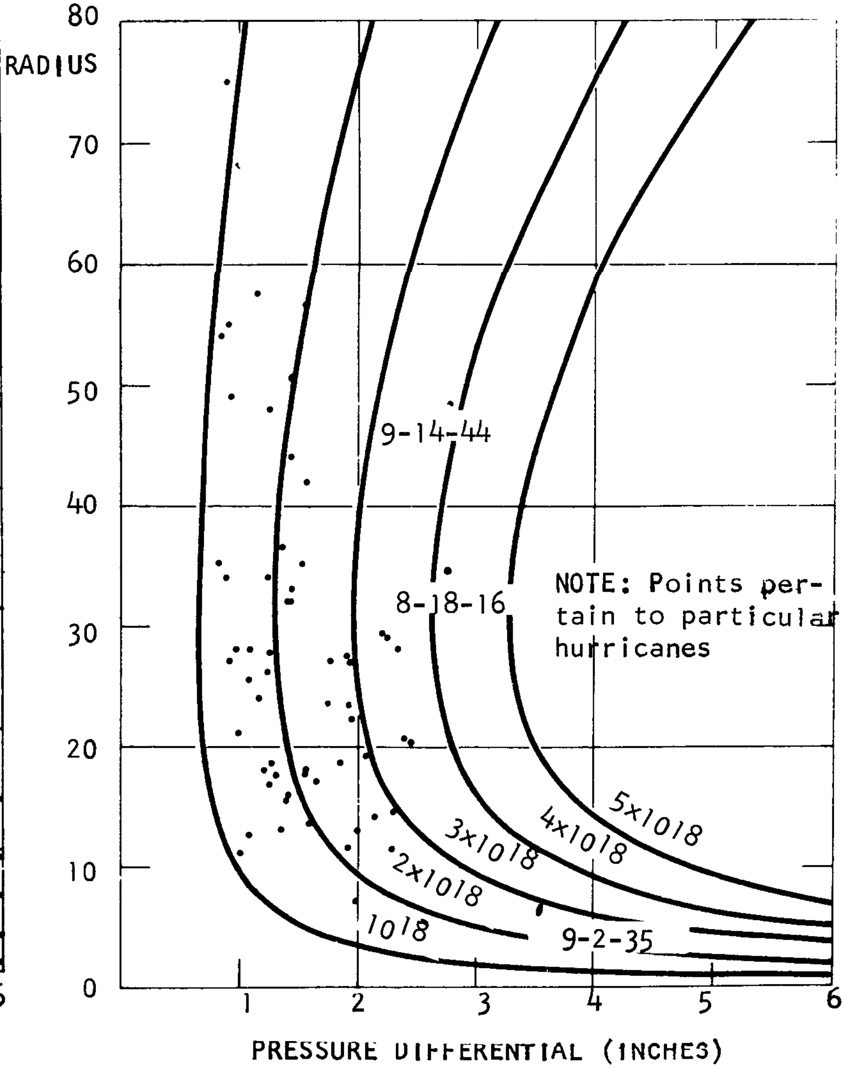
---

*Lowest central pressure and highest wind speed ever recorded in U.S.

FIGURE E.1



KINETIC ENERGY (ERGS) IN A CIRCULAR LAYER OF 100-NAUTICAL-MILE RADIUS, 1 CM DEEP, AS A FUNCTION OF STORM RADIUS AND PRESSURE GRADIENT



KINETIC ENERGY (ERGS) IN A CIRCULAR LAYER OF 50-NAUTICAL-MILE RADIUS, 1 CM DEEP, AS A FUNCTION OF STORM RADIUS AND PRESSURE GRADIENT

FIRES

Large historic fires provide some useful background for making comparisons with fires ignited by nuclear weapons. Also, the smoke produced by large fires is in some ways analogous to fallout.

The energy released into the atmosphere by fires is small compared to other natural events--about 4×10^9 calories per ton of fuel per acre. Assuming an average fuel density of 20 tons per acre, this amounts to 8×10^{10} calories (per acre or about 50 KT/mi^2). Thus the total energy released by the greatest forest fire in the history of the U.S. (Michigan-Wisconsin, October 1871) was about 300 MT.

The energy calculations are made on the basis of 20 tons/acre. This is extremely crude, and common sense immediately suggests that the Tillamook fire (virgin Douglas Fir) probably burned much more fuel than typical fires in logged areas. However, the complexities are such that better estimates do not seem to be available at present.

There have probably been some larger fires in other parts of the world. In particular, there have been some tremendous forest fires in Siberia for which, however, we have little information.

The smoke accompanying forest fires does not seem to have attracted much attention to date, except insofar as it helps or hinders detection of forest fires. However, most people will recall days with very hazy skies attributable to distant fires. Stonier[40] cites a case in point: on September 25-26, 1950, the insolation (sunlight reaching the earth) in Washington, D.C., was only 52% of normal although the days were cloudless, as a consequence of forest fires in western Canada. The smoke pall covered the eastern seaboard of the U.S. and stretched as far as Europe. Evidently fires are rather efficient at producing widespread haze in comparison with other mechanisms (e.g., volcanoes). However, little is known about the details.

A list is given on the following page as Table E-6.

Table E-6

Fires[41]

Area	Dates	Cause of Ignition and Spread	Area Mi.^{2}	Energy Released MT
Eastern Wisc. (Peshtigo) & Central Mich.	Oct. 8, 1871	Merging of many small logging fires; long drought, high winds	5900	300
Miramichi (New Brunswick) & Maine	Oct. 7, 1825	Merging of many small logging fires; long drought, high winds	4700	240
Idaho	Aug. 10-21, 1910	Merging of many small logging fires; long drought, high winds	4700	240
Ft. Yukon, Alaska	1950	--	2500-3500	130-180
Wisconsin & Hinckley, Minn.	Aug.-Sept., 1894 Sept. 1, 1894	Merging of many small logging fires; long drought, moderate winds	2000-3000	100-150
Yacoult-West. Washington & Oregon	Sept. 12-13, 1902	Merging of many small logging fires; long drought, moderate to strong winds. Over 110 separate large fires.	1500-2000	75-100
E. Michigan	Sept. 1-5, 1881	Merging of many small logging fires; long drought, moderate winds. Some lightning fires.	1500	75
Adirondacks, N.Y.	Primarily May 28-June 3, 1903	Merging of fires from campers, incendiaries. Dry spring; strong winds.	1000	50

Table E-6

Fires (Continued)

Area	Dates	Cause of Ignition and Spread	Area Mi.^{2}	Energy Released MT
Tillamook, Ore.	Aug. 14-25, 1933	2 ignition points; long drought. Fire burned slowly until hot gale force winds on Aug. 24-25.	486 (420 mi. in 20 hours)	24
Maine (Mt. Desert Isl.)	Oct. 1957	2 ignition points; long drought.	375	19
Maine	Oct. 21-25, 1947	Long drought, many small fires, low humidity, high winds (50 fires burning).	320	16

City fires of great extent have occurred throughout history. For example, one might include the following:

Table E-7

City Fires

Location	Date	Origin of Fire	Extent of Damage
London[42]	Sept. 2-4, 1666	Possibly originated with fires deliberately started to burn down plague houses. Dry summer, strong NE wind.	2 mi.^{2} area 13,000 houses destroyed (80% of city)
Moscow[43]	Sept. 14-19, 1812	Russians set fire to deny the city to Napoleon.	30,800 houses destroyed (90% of city
Hamburg[44]	May 5-7, 1842	City was in state of anarchy during the fire which lasted 100 hours.	4,219 buildings destroyed (20% of city)
Chicago[45]	Oct. 8-10, 1871	Long drought; hot dry winds. (Same day as Peshtigo, Wisc. forest fire.)	3.3 mi.^{2} area burned. 17,450 buildings destroyed
Honolulu[46]	Jan. 15, 1900	Fires deliberately started to burn plague areas in Chinatown: got out of control.	--
San Francisco[47]	Apr. 18, 1906	Aftermath of earthquake	4 mi.^{2} area burned (95% of over-all damage was due to fire)

Table E-7

City Fires (Continued)

Location	Date	Origin of Fire	Extent of Damage
Yokohama-Tokyo[48]	Sept. 1, 1923	Aftermath of earthquake.	447,128 houses destroyed (95% of Yokohama, 71% of Tokyo)
Hamburg[49]	July 24-28, 1943	Incendiary attack by Royal Air Force.	5 mi.^{2} area burned 214,000 houses and 4,300 factories destroyed
Dresden[50]	Feb. 13-14, 1945	Incendiary attack by Royal Air Force. Prototype "fire storm."	6.7 mi.^{2} (>25% destruction) 28,000 buildings damaged or destroyed* (80% of city)
Tokyo[51]	Mar. 9, 1945	Incendiary attack by U.S. Air Force.	17 mi.^{2} burned

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APPENDIX F

DESTRUCTIVENESS VS. FREQUENCY OF FIRES

Assume there are k "ignition points" resulting in discrete fires at a given time, and let f(i,k) be the number of such fires which destroy precisely i "cells" (e.g., acres). Then the probability that the next cell will be destroyed by a fire which has already destroyed i cells is taken to be

$$i\ f(i,k)$$

while the probability that the next cell will be destroyed by a fire which has thus far destroyed no cells (i.e., a new ignition point is created) is taken to be a constant α. Since the total number of ignition points, k, is assumed to remain constant, each time a new one is created another is dropped from consideration. The probability that the fire thus removed from the distribution is one which has burned i cells (or acres) is proportional to the number of such fires, viz.,

$$f(i,k).$$

These assumptions determine the form of the f(i,k) completely for large values of k, namely

$$\lim_{k \longrightarrow \infty} f(i,k) = f(i) = \frac{A\Gamma(i)\ \Gamma\left(\frac{2-\alpha}{1-\alpha}\right)}{\Gamma\left(\frac{2-\alpha}{1-\alpha} + i\right)}$$

where $\Gamma(z)$ is the well-known factorial function.[1] In the "tail" of the distribution, i.e., for large values of i, this function is approximately given by

$$\lim_{i \longrightarrow \infty} f(i) \cong \frac{A\Gamma\left(\frac{2-\alpha}{1-\alpha}\right)}{\Gamma\left(i + \frac{2-\alpha}{1-\alpha}\right)} = \frac{A\Gamma(p)}{i^p}$$

where $p = 2-\alpha/1-\alpha$.

A distribution of this form was first derived from a probability model by G.U. Yule (1924)[2] to explain the distribution of species among biological genera. If one were to plot f(i) vs. i in the normal way, the distribution would decrease, from a maximum at the origin, asymptotically towards zero. Of course, for finite k, there is one largest fire which burns an area i_{max} and f(i) must be zero identically for $i > i_{max}$. This is, of course, the interesting region of the curve, since it was pointed out previously that most of the damage is done by a very small fraction of the fires. Hence it is more useful to plot i vs. f(i) or--for convenience--log i vs. log f(i), as in Figure F.1, since the result will theoretically be a straight line with (negative) slope 1/p. The two parameters p,A are easily determined in principle by means of an empirical plot of log i vs. log f(i), assuming the data come reasonably close to fitting the theoretical curve.

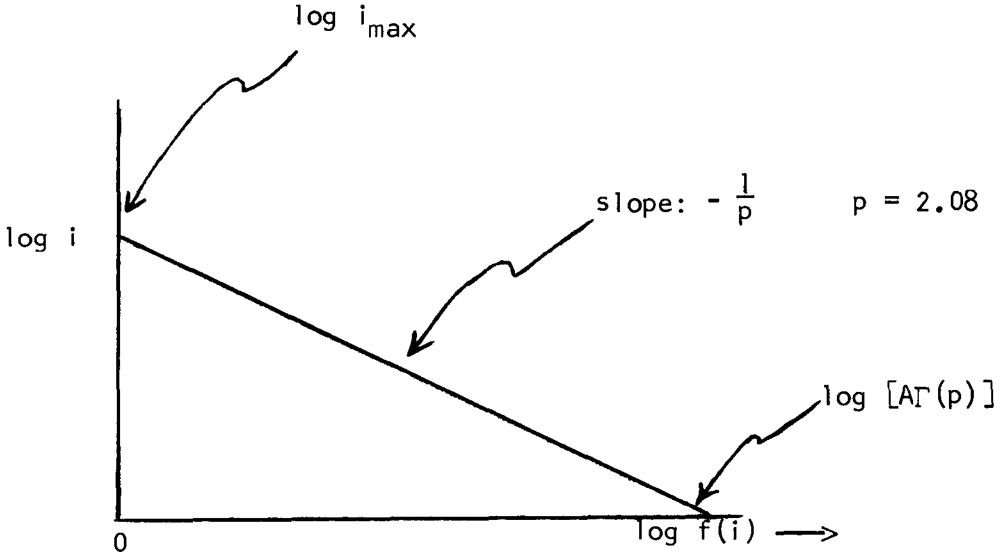
Total number of fires:

$$k = \sum_{i=1}^{i_{max}} f(i,k) \cong A\Gamma(p)\,\zeta(p)$$

where $\zeta(p)$ is the Reimann ζ-function.[3]

FIGURE F.1

FREQUENCY OF OCCURRENCE OF FIRES AS A FUNCTION OF DAMAGE INDEX



Total number of cells (acres) destroyed by fire:

$$n = \sum_{i=1}^{i_{max}} i\ f(i,k) \cong A\Gamma(p)\,\zeta(p-1)$$

Let κ be the fraction of all fires which exceed a given size i_t

$$\kappa k = \sum_{i=i_t}^{i_{max}} f(i,k) \cong \int_{i_t}^{i_{max}} f(i)\,di \cong \frac{A\Gamma(p)}{p-1}\ \frac{1}{i_t^{\,p-1}}$$

and let η be the fraction of all damage done by fires greater than i_t

$$\eta n = \sum_{i=i_t}^{i_{max}} i\ f(i,k) \cong \frac{A\Gamma(p)}{p-2}\ \frac{1}{{i_t}^{p-2}}$$

We shall not reproduce the remainder of the analysis, which is essentially a process of manipulating numbers. The results, which can be verified directly, are that

$$p \approx 2.07$$

almost regardless of the exact values of η, κ and i_t, provided the average number of acres per fire (η/κ) is fixed. We have tentatively taken this number to be 34, as derived from Table 2-7 for the average of the years 1957-1959. The results are not sensitive to the other parameters, within reasonable limits, but it is obvious that η will be a large fraction, since

$$\eta \cong \frac{1}{0.08\ \zeta(1.08)\ {i_t}^{0.08}}$$

while κ will be a small fraction, since

$$\kappa \cong \frac{1}{1.08\ \zeta(2.08)\ {i_t}^{1.08}}$$

These conclusions are consistent with the known facts (i.e., 75-90% of the damage is due to 3-7% of the fires).

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Volume I summarizes current knowledge of the effects of nuclear weapons on area targets. Radiological effects are divided roughly into three categories: external γ-radiation from fallout fields; external β-burns and internal hazards due to cycling of Sr-90, Cs-137 and I-131. Vulnerabilities of different classes of targets or "biomes" are considered, e.g. vertebrates, insects, conifer forests, deciduous forests, grasslands and crop lands. Thermal ignition and probabilities of fire spread under various conditions are discussed in Chapter II. Chapter III is concerned with potential meteorological and climatic problems. Chapter IV discusses a variety of "second-order" problems such as epidemics, pest outbreaks, floods, erosion and ecological changes.

Volume II is devoted to an analysis of the interactions of these effects with postattack recovery problems, particularly in connection with agriculture. The potential conflicts between short-term and long-term objectives are stressed. A number of specific countermeasures are listed and discussed.

Volume III is a short summary of the whole report, bound separately for convenience.

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